



## UNITED STATES AIR FORCE RESEARCH LABORATORY

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### Field Studies of Habituation to Change in Nighttime Aircraft Noise and of Sleep Motility Measurement Methods

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## FOR THE COMMANDER



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Chief, Crew System Interface Division  
Air Force Research Laboratory

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## PREFACE

The work reported herein was performed by BBN Technologies of Canoga Park CA under Air Force contract F41624-96-C-9003 during the period December 1995 to March 1998. The work was performed under Program Element 63723F, work unit 2103C2B1 for the Aural Displays and Bioacoustics Branch, Crew System Interface Division of the Air Force Research Laboratory at Wright-Patterson AFB, OH. Mr. Larry Finegold was the Air Force project monitor.

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# 1 EXECUTIVE SUMMARY

This report describes studies of the sleep quality of residents near a large general aviation airport during a short-term increase in nighttime aircraft noise, and of actimetric measurements of sleep motility in epochs of varying duration. A total of 686 subject-nights of observations suitable for full analysis of indoor and outdoor noise levels, in-bed motility, behaviorally-confirmed awakenings, and self-reported awakenings were made in residences of test participants in a neighborhood near DeKalb-Peachtree Airport (PDK) in the Atlanta, Georgia metropolitan area. An additional 117 subject-nights of motility measurements were made in both familiar and unfamiliar sleeping quarters in epochs of 2 second and longer durations to explore methodological issues.

## 1.1 BACKGROUND

Little of what is known about the prevalence of noise-induced sleep disturbance (*cf.* Pearsons, Barber, Tabachnick, and Fidell, 1995) in airport neighborhoods addresses the time course of response to changes in nighttime aircraft noise exposure. Although several large-scale field studies of aircraft noise-induced sleep disturbance have been conducted in recent years (*e.g.*, Ollerhead, Jones, Cadoux, Woodley, Atkinson, Horne, Pankhurst, Reyner, Hume, Van, Watson, Diamond, Egger, Holmes, and McKean, 1992; Fidell, Pearsons, Howe, Tabachnick, Silvati, and Barber, 1995a; and Fidell, Howe, Tabachnick, Pearsons, and Sneddon, 1995b), many of these field observations were made under stable conditions of aircraft noise exposure, among airfield vicinity residents familiar with both their sleeping quarters and routine neighborhood aircraft activity. The paucity of information about adaptation to changes in nighttime noise is due in large part to the rarity of appropriate settings for field study of habituation to major changes in aircraft noise-induced sleep disturbance.

## 1.2 DOSAGE-RESPONSE STUDY

Air traffic associated with the Olympic Games held in Atlanta, Georgia from 17 July through 4 August 1996 increased aircraft operations at airfields in the Atlanta metropolitan region markedly, forcing many flights to arrive and depart at off-peak hours, especially in the late evening and early morning hours. FAA approved a number of air traffic control measures that permitted regional airports such as PDK to handle much of this additional air traffic, and incidentally created a potential opportunity to observe the time course of habituation of sleep disturbance in a residential population to short-term changes in nighttime aircraft noise.

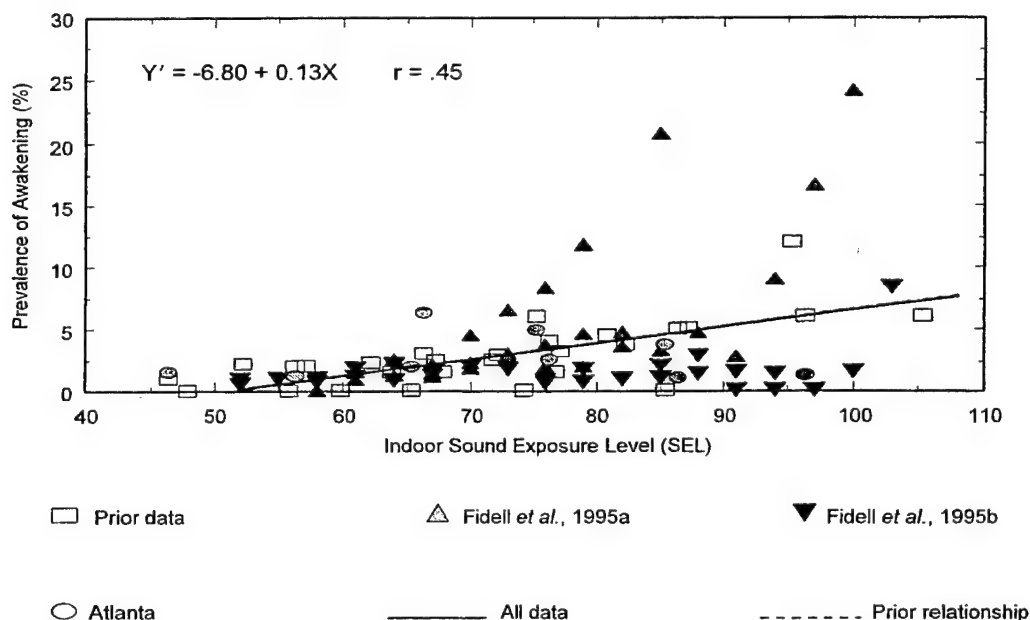
Both behavioral awakening and motility measurements were therefore made over a six week period in residences near PDK: eighteen days prior to the Olympic Games held in Atlanta, Georgia, the seventeen days of their conduct from 17 July through 4 August 1996, and one week after their conclusion. Noise levels produced by aircraft and other sources were monitored both outdoors and within sleeping quarters.

### 1.3 METHODOLOGICAL STUDY

A secondary goal of the current study was to investigate the sensitivity of sleep motility (bodily movement during sleep, as measured by wrist-worn recording accelerometers, or actimeters) to noise-induced disturbance in analysis epochs of various durations. Indoor noise exposure and actimetric activity were measured during eleven nights from eight test participants sleeping in unfamiliar quarters; over a six week period from ten test participants in their residences near Los Angeles International Airport; and over a four week period in the homes of nine other test participants. Since this latter data collection effort was focused on a methodological issue concerning interpretation of actimetric measurements, fewer efforts were made to collect information about button pushing responses and outdoor noise levels for dosage-response relationships between aircraft noise and sleep disturbance.

### 1.4 SUMMARY OF CURRENT FINDINGS

Figure 1 compares the findings of the present observations of behavioral awakening (filled circular plotting symbols) with a dosage-response relationship inferred from all recent large-scale field studies of sleep disturbance associated with nighttime aircraft noise. The present findings are consistent with the results of these prior studies. The prevalence of behavioral awakening increases by about 1.3% for every 10 dB increase in indoor sound exposure level of individual events. About 20% of the variance in indoor SEL and the prevalence of behavioral awakening is shared in the combined data set.



**Figure 1** Relationship of present to prior findings. (Prior data include Ollerhead *et al.* 1992 and Pearsons *et al.* 1995. Prior relationship excludes Atlanta data.)

Current results show no reliable dosage-response relationship among motility (actimetric zero crossings), *awakening*, and either indoor or outdoor noise event level. In other words, motility did not predict awakenings. This is inconsistent with a prior finding that the probability of motility increased by about 4% with each 10 dB increase in indoor SEL (Fidell *et al.*, 1995b).

When a criterion for *arousal* is applied to the actimetric data, about 40% of the variance in arousal is associated with sound level. The probability of arousal is increased by about 5% with each 10 dB increase in indoor SEL. This is consistent with the shared variance found by Fidell *et al.* (1995b) in which the probability of arousal increased by about 3% with each 10 dB increase in indoor SEL.

The pattern of findings of the methodological study of motility measurement revealed little practical benefit of analyzing motility measurements in short duration epochs.

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## 2 INTRODUCTION

Aircraft noise-induced sleep disturbance in airport neighborhoods is a matter of topical interest for environmental assessment and regulatory purposes both in the United States and elsewhere (*cf.* Health Council of the Netherlands, 1997; Öhrström, 1993; Öhrström and Griefahn, 1993). While no fully satisfactory dose-response relationship exists for predicting sleep disturbance from noise exposure in residential settings (FICON, 1992; Pearsons, Barber, Tabachnick, and Fidell, 1995), several recent field studies have increased the stock of information about this issue (*e.g.*, Ollerhead *et al.*, 1992; and Fidell *et al.*, 1995a and 1995b).

The studies of Ollerhead *et al.* and of Fidell *et al.* focused on different aspects of sleep disturbance and differed in details of noise measurement. These latter data sets included behavioral indications of sleep disturbance, however, and produced roughly comparable findings. Fidell *et al.* (1995b) took advantage of an expected change in aircraft operations brought about by the closure of a major civil airport and the opening of another nearby to observe habituation to aircraft noise-induced sleep disturbance. Conduct of the Olympic Games in Atlanta, Georgia and the consequent increase in aircraft operations and air traffic at regional airports presented a second potential opportunity to study the time course of habituation to noise-induced sleep disturbance.

Two separate sets of field measurements were made in the course of the present study. An initial set of field measurements, intended to yield information useful for defining a dosage-response relationship between noise exposure and sleep disturbance, was made in conjunction with anticipated changes in aircraft noise exposure associated with the Olympic Games in Atlanta, Georgia during July and August of 1996. Behavioral awakening and motility measurements, outdoor measurements of aircraft noise, and indoor measurements of household noise in test participants' sleeping quarters in residences near DeKalb-Peachtree Airport (PDK), a large general aviation airport, were made in the first round of data collection. Measurements were taken for 18 days prior to the start of the Olympic Games, during the 17 days of their conduct, and for one week after their conclusion. Behavioral awakening was measured in a manner identical to that described by Fidell *et al.* (1995a and 1995b).

A meeting of a technical committee of the Acoustical Society of America (S-12 Working Group 37, "Measuring Sleep Disturbance Due to Noise," U.S. accredited Standards Committee on Noise, Technical Advisory Group ISO/TC 43/SC1), held as data collection was completed in Atlanta, identified concerns among some sleep researchers about the interpretation of sleep motility data collected in 30-second epochs. Several European sleep researchers suggested that actimetric indications of sleep disturbance could be discerned more clearly in analysis epochs shorter than 30 seconds.

Ollerhead *et al.* had selected a duration of 30 seconds for motility analysis epochs for pragmatic reasons, in part because of difficulties in processing larger quantities of data in shorter epochs, and in part because a 30-second epoch corresponds to the conventional frame length of EEG measurement. The efforts of Ollerhead *et al.* to relate EEG and actimetric measurements of arousal to one another were only partially successful. Ollerhead *et al.* believed that about 40% of arousals

inferred from highly processed motility data represented awakenings, but were unable to distinguish "arousals" (shifts from deeper to lighter sleep) from "awakenings" (departure from an intuitively reasonable definition of sleep) despite extensive analysis. Further, the number of awakenings predicted by their actimetric criteria after the 40% adjustment was still far in excess of the number of behaviorally-confirmed awakenings observed by Fidell *et al.* (1995a).

A second set of sleep motility measurements was therefore begun in October 1996 for methodological purposes rather than for purposes of defining a dosage-response relationship between noise exposure and sleep disturbance. Wrist-worn actimeters were configured in this latter study to collect information about crossings of a threshold of arm movement during intervals two seconds in duration. Epochs of greater duration were constructed analytically from these short intervals during data reduction. The field observations of sleep motility in epochs of short duration were made under a range of conditions of noise exposure and familiarity with sleeping quarters.

### 3 METHOD

This section describes procedures used to select sites, to measure noise exposure, and to collect, reduce and analyze sleep disturbance and motility data.

#### 3.1 STUDY SITES AND DATA COLLECTION SCHEDULES

Observations of noise exposure and sleep disturbance in the primary dosage-response study were made in 12 single-family detached homes to the north of PDK.<sup>1</sup> Motility data were collected at three sets of sites in the subsequent study: (1) a large motor home located approximately 40 miles to the southeast of Fallon NAS, in which field data collection personnel acted as test participants; (2) five single-family detached homes to the north of LAX; and (3) four single-family detached homes in quiet suburban areas. Table 1 summarizes the data collection schedule.

**Table 1** Summary of data collection schedule and sizes of analyzable data sets.

| SITE                              | TIME FRAME                   | NUMBER OF RESIDENCES | NUMBER OF TEST PARTICIPANTS | SUBJECT-NIGHTS |
|-----------------------------------|------------------------------|----------------------|-----------------------------|----------------|
| De Kalb-Peachtree Airport         | July - August 1996           | 12                   | 22                          | 686            |
| Unfamiliar Sleeping Quarters      | October 1996                 | 1                    | 8                           | 29             |
| Los Angeles International Airport | December 1996 - January 1997 | 5                    | 10                          | 50             |
| Suburban Sites                    | January - February 1997      | 4                    | 8                           | 38             |
| TOTAL                             |                              | 22                   | 48 *                        | 803            |

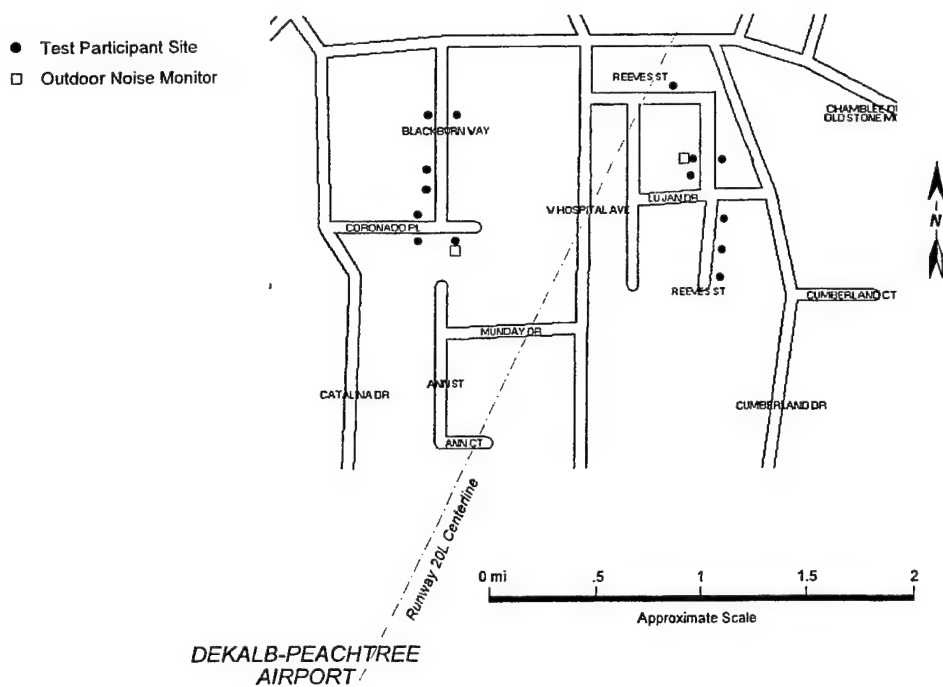
\* The number of unique test participants was 43. BBN staff participated both in the unfamiliar sleeping quarters and at the suburban sites.

##### 3.1.1 Data Collection at PDK

Data collection began in a residential area north of PDK on 2 July 1996, 15 days prior to the opening ceremony of the Olympic Games, continued through the Games, and ended one week after their conclusion. Efforts were made to measure noise exposure and sleep disturbance in 14 residences.<sup>1</sup> Figure 2 shows the locations of test participants' homes and outdoor noise monitoring sites in areas to the north of PDK.

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<sup>1</sup> Although 25 residents in 14 homes were selected initially for measurements of noise exposure and sleep disturbance, data screening reduced the number of participants considered in the data analyses to 22 residents in 12 homes.



**Figure 2** Locations of test participants' homes and outdoor noise monitoring sites at PDK.

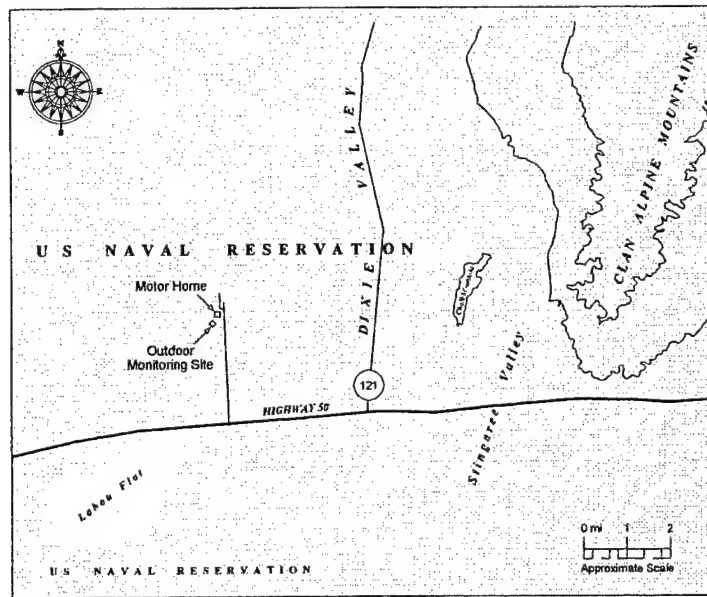
### 3.1.2 Data Collection in Unfamiliar Sleeping Quarters

Data collection was planned to coincide with military flight training operations scheduled for October 1996, at a military training range in the Dixie Valley approximately 40 miles southeast of Fallon Naval Air Station, NV. A motor home was installed at a location selected for its proximity to the training range. Data collection began on 21 October and continued through 31 October. Figure 3 shows the location of the motor home and the nearby outdoor noise monitoring site.

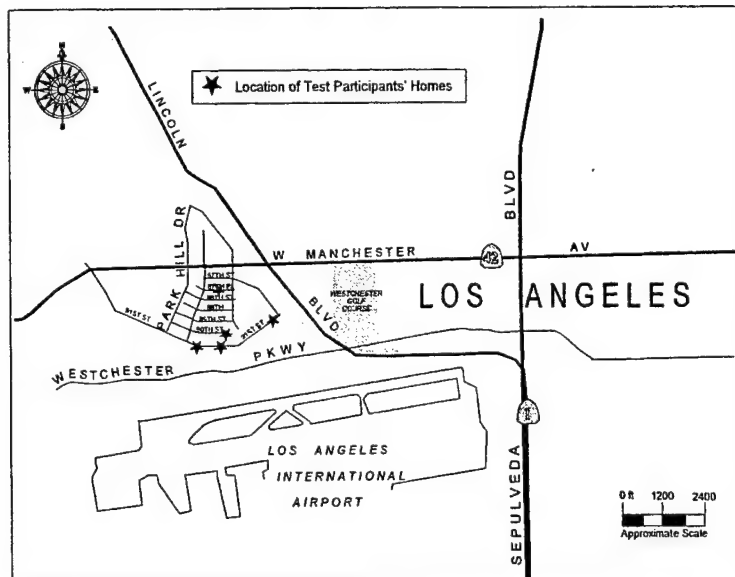
### 3.1.3 Data Collection Near Los Angeles International Airport

A residential neighborhood north of LAX was selected for the second site because of its proximity to a major airport and its proximity to BBN's Canoga Park office.<sup>2</sup> Data collection began on 9 December 1996 and ended on 24 January 1997. Figure 4 shows the locations of the test participants' homes and the outdoor noise monitoring site.

<sup>2</sup> Actigraphs were programmed to collect data in 2-second epochs, effectively exhausting their data storage capacity overnight. This necessitated either daily downloads of the actigraphs, or provision of multiple, serially-programmed actigraphs for each test participant for weekly downloading. The frequency of maintenance visits made proximity to BBN's office essential for cost-effectiveness in data collection.



**Figure 3** Location of motor home and outdoor noise monitoring site southeast of Fallon NAS.



**Figure 4** Location of test participants' homes at LAX.

### **3.1.4 Data Collection at Suburban Sites**

Motility data were collected from four couples sharing sleeping quarters in four residences in quiet suburban areas of Los Angeles over the period from 30 January 1997 to 23 February 1997.

## **3.2 TEST PARTICIPANTS**

Observations of sleep disturbance of a total of 46 different people were made in the course of this field study: 25 near PDK, and 21 at other sites.<sup>3</sup> BBN staff participated as subjects in the motility study in both the unfamiliar and familiar sleeping quarters.

### **3.2.1 DeKalb-Peachtree Airport, GA**

Test participants were recruited through mailings to residences within address ranges determined by a site visit. Address lists were assembled from direct observation of street addresses and reverse telephone directories. The mailing included letters describing the study and a return form for those interested in participation and able to provide informed consent. Follow-up of returned indications of interest was accomplished by telephone. The constraints of spatial distribution of aircraft noise exposure, presumed self-selection biases of neighborhood residence, and small numbers of eligible households and test participants precluded efforts to obtain a random sample. Details of recruitment procedures may be found in Appendix A.

Selection of households in residential areas north of PDK was made on the basis of the following overall requirements and preferences wherever possible:

- approximately equal numbers of men and women;
- at least two people participating in each household;
- a range of ages, from young adults (at least 18 years old) to the elderly;
- neighborhood residence for at least three months;
- good general health;
- households in which occupants of shared sleeping quarters were likely to be present for all test nights; and
- households with differing ambient noise environments in sleeping quarters.

No formal determination of hearing acuity was made. Potential test participants who were observed to have difficulty using the telephone or understanding other spoken communication were not permitted to take part in the study.

### **3.2.2 Motility Measurements in Unfamiliar Sleeping Quarters**

Eight members of a field measurement crew (BBN staff members and research assistants) took part in this phase of the motility study. Participants were rotationally-based in a motor home

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<sup>3</sup> Data screening later reduced the total number of unique test participants for whom data were included in the analyses to 43.

located in the Dixie Valley, approximately 40 miles southeast of Fallon Naval Air Station, NV. Test participants lived in the motor home for two to five days during a two-week period. Participants included both men and women whose ages ranged from early twenties to early sixties. All participants were in good health and had adequate hearing acuity.

### 3.2.3 Motility Measurements in Familiar Sleeping Quarters

Ten test participants at the second site in the methodological investigation were recruited by telephone. Residents of five single-family, detached homes in the vicinity of LAX provided informed consent for participation in this study.<sup>4</sup> An additional set of eight test subjects, consisting of BBN staff and adult family members, participated in this phase of the study over the course of five weeks.

## 3.3 NOISE MEASUREMENTS

### 3.3.1 Noise Measurements at PDK

Instrumentation assembled to support automated capture, processing, and analysis of large amounts of noise exposure information is depicted in Figure 5. This instrumentation preserved time synchronization among data streams for time series of A-weighted sound pressure measurements recorded indoors and outdoors, awakening responses from test participants' hand switches, and motility measurements from actimeters.

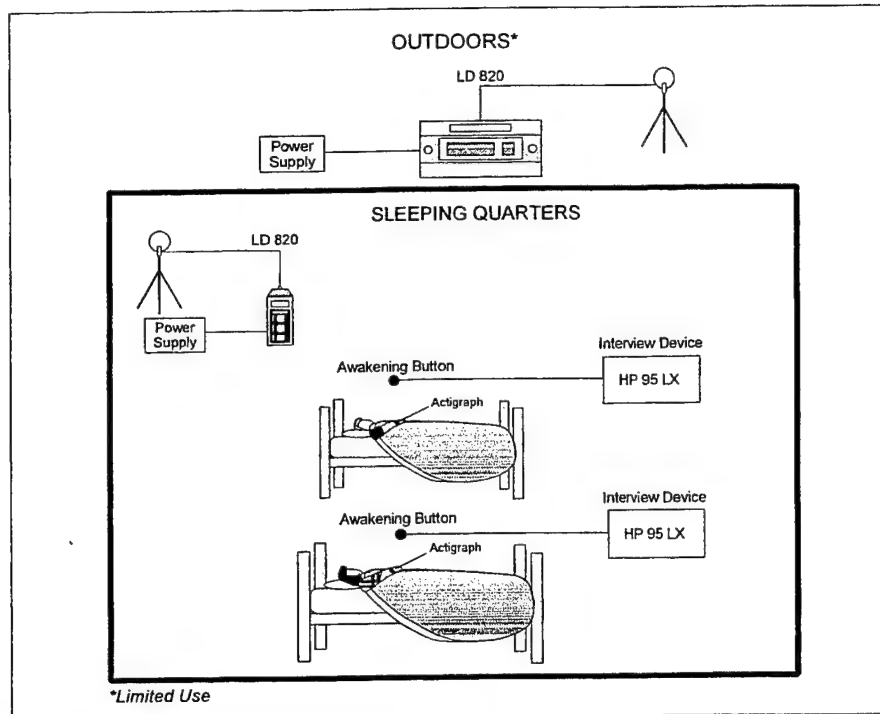
Indoor digital noise measurements with microphones in test participants' sleeping quarters were made continuously with Larson-Davis 820 noise monitors for the six week data collection period. Continuous 2-second time histories were recorded, as were hourly TAVA values. Levels associated with noise events were stored in the noise monitors during the entire measurement period. Noise events were defined as a time series of noise levels that began when a pre-set threshold was exceeded for at least 10 seconds, and that continued until the level remained more than 2 dB below the pre-set threshold. The threshold for indoor locations in this study was an A-weighted sound level of 50 dB.<sup>5</sup> All of the noise monitors were equipped with modems to permit remote data capture. Telephone lines were installed in all but one test participant's sleeping quarters at the beginning of the data collection process. Noise monitors for which telephone lines were installed were downloaded every two or three days; the remaining noise monitor was downloaded during weekly visits to test participants' homes for other equipment maintenance purposes.

Outdoor noise measurements were made in the vicinity of all test participants' homes with two Larson-Davis 820 noise monitors, with the same parameters used to collect indoor noise data, except for the outdoor threshold, which was set to an A-weighted level of 60 dB.

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<sup>4</sup> The ten test participants recruited for the motility study near Los Angeles International Airport had participated as subjects in a prior Air Force study of sleep disturbance (Fidell *et al.*, 1995a).

<sup>5</sup> Indoor and outdoor noise event 2-second thresholds were typically set at 60 and 70 dB, respectively, in the field observations described by Fidell *et al.* (1995b).



**Figure 5** Schematic diagram of field instrumentation.

### 3.3.2 Noise Measurements in Unfamiliar Sleeping Quarters

Indoor noise measurements were made continuously with a Larson-Davis 820 noise monitor for the eleven-day data collection period, with a microphone placed inside test participants' sleeping quarters. Continuous 2-second time histories were recorded, as were hourly TAVA values. Noise events as defined in Section 3.3.1 were also stored in the monitor. The indoor noise monitor was downloaded once per week.

Outdoor noise measurements were made in the vicinity of the motor home with one Larson-Davis 820 noise monitor, using the same parameters employed to collect indoor noise data except that the threshold was set to an A-weighted level of 60 dB.

### 3.3.3 Noise Measurements in Familiar Sleeping Quarters

Indoor noise measurements were made continuously for five days at each of five homes, for five (non-consecutive) weeks, with a Larson-Davis 820 noise monitor. A microphone was placed inside test participants' sleeping quarters. Continuous 2-second time histories were recorded, as were hourly TAVA values. The indoor noise monitor was downloaded once per week. No outdoor noise measurements were made in this data collection phase.

## 3.4 RESPONSE MEASUREMENTS

A palmtop computer (HP-95LX) was provided to each test participant to administer the evening and morning questionnaires, samples of which may be found in Appendix A. A pushbutton

attached by a short cable to the computer served as the means to confirm behavioral awakening during the night. Nighttime motility was recorded via actigraphs.

### **3.5 MOTILITY MEASUREMENTS**

MiniMotion Logger recording accelerometers ("actigraphs," manufactured by Ambulatory Monitoring, Inc.) counted and stored the number of times a voltage produced by vertical motion of the wrist-worn device exceeded a reference value during a 2-second interval. The reference voltage corresponded to approximately 0.002 g at frequencies below about 3 Hz. Each such count is referred to as a zero crossing. Measurements of indoor noise levels in test participants' sleeping quarters were also made in synchronous intervals between 2200 and 0700 hours.

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## 4 RESULTS OF STUDY AT PDK

This chapter describes findings of analyses of indoor and outdoor sound levels, motility measurements, behaviorally confirmed awakenings (button pushes), self-reports of sleep disturbance, and relationships among them.

### 4.1 OVERVIEW OF DATA PROCESSING AND ANALYSES

Informed consent was obtained from 25 residents of 14 homes to participate in this study. Data from participants who were inconsistent in their use of the equipment or whose equipment malfunctioned were not considered in the analyses. Data screening reduced the number of participants considered in the data analyses to 22 residents of 12 homes. Indoor noise event levels were measured in sleeping quarters, while outdoor event levels were estimated from measurements made at the closer to a participant's house of the two outdoor measurement locations.

Table 2 shows the numbers of subject nights of observations made in the periods before, during, and after the Olympic Games. Table 3 summarizes the analyses performed on these data. Simple descriptive accounts of findings are presented in this section. Data sets are described in Sections 4.2 and 4.3. More detailed inferential analyses begin in Section 4.4.

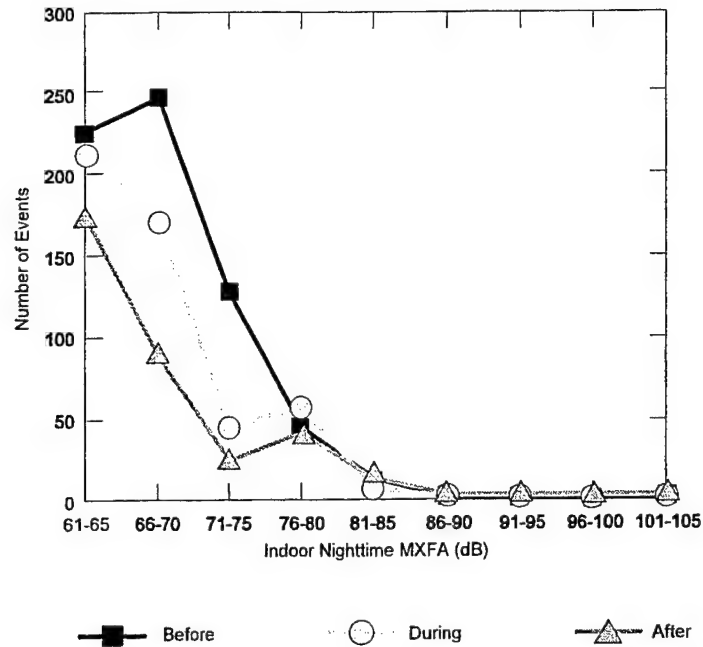
**Table 2** Summary of data collection.

| DATA COLLECTION PERIOD                    | SUBJECT-NIGHTS OF DATA COLLECTION |
|---|-----------------------------------|
| Before Olympics (2 - 16 July 1996)        | 312                               |
| During Olympics (17 July - 4 August 1996) | 318                               |
| After Olympics (5 - 11 August 1996)       | 98                                |
| Total                                     | 728*                              |

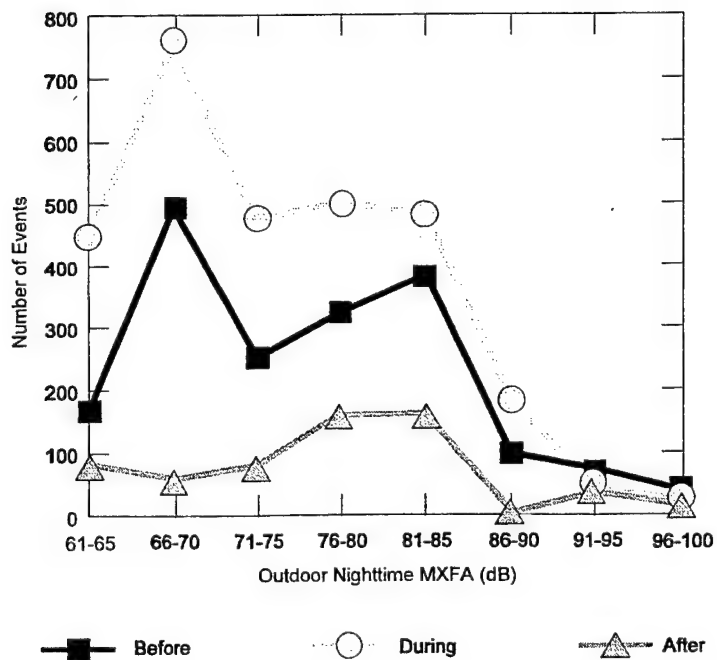
\* Data screening reduced the analyzable subject-nights to a total of 686.

### 4.2 DESCRIPTION OF INDOOR AND OUTDOOR NOISE ENVIRONMENTS

Figures 6 and 7 illustrate the distributions of maximum levels of noise events recorded between 2200 and 0700 hours indoors and outdoors near PDK before, during, and after the Olympics. Tables 15 through 17 in Appendix B summarize the indoor and outdoor noise environments during each data collection period for each household.



**Figure 6** Distribution of noise event levels recorded inside test participants' sleeping quarters between 2200 and 0700 hours in three measurement periods.



**Figure 7** Distribution of outdoor noise event levels between 2200 and 0700 hours in three measurement periods.

**Table 3** Guide to analyses performed on data collected near PDK.

| ANALYSIS   | DATA SET  | RESULTS SECTION |
|--|---|-----------------|
| <b>DESCRIPTIVE ANALYSES</b>  |   |                 |
| Indoor and outdoor noise environments  | Before Olympics — event data                          | 4.2.1           |
| Indoor and outdoor noise environments  | During Olympics — event data                          | 4.2.2           |
| Indoor and outdoor noise environments  | After Olympics — event data                           | 4.2.3           |
| Relationship between indoor and outdoor noise levels                                 | All time periods — all night data                     | 4.2.4           |
| Behavioral awakenings and questionnaire responses                                    | Before Olympics — all night data                      | 4.3.1           |
| Behavioral awakenings and questionnaire responses                                    | During Olympics — all night data                      | 4.3.2           |
| Behavioral awakenings and questionnaire responses                                    | After Olympics — all night data                       | 4.3.3           |
| <b>INFERENTIAL ANALYSES</b>  |   |                 |
| Dosage-response analysis   | All time periods — events between 2200 and 0700 hours | 4.4.1           |
| Temporal adaptation of awakenings, latency and motility                              | All time periods — all night data                     | 4.4.2           |
| Indoor and outdoor TAVA before, during, and after Olympics                           | All time periods — all night data                     | 4.4.2           |
| Analysis of variance on indoor and outdoor TAVA                                      | All time periods — all night data                     | 4.4.2           |
| Relationship between and behavioral awakening responses and arousals                 | All time periods — outdoor event data                 | 4.4.3.1         |
| Relationship between behavioral awakening responses and motility                     | All time periods — outdoor event data                 | 4.4.3.2         |
| Relationship between behavioral awakening responses and recalled awakenings          | All time periods — all night data                     | 4.4.3.3         |
| Prediction of behavioral awakening responses from noise levels and control variables | All time periods — outdoor event data                 | 4.4.4.1         |
| Prediction of arousal responses from noise levels and control variables              | All time periods — indoor event data                  | 4.4.4.2         |

#### 4.2.1 Noise Environment Before Start of Olympics

Table 15 in Appendix B summarizes the test participants' nighttime noise environment for the data collection period before the start of the Olympics (29 June-16 July 1996). A total of 977 noise events, from as few as 7 to as many as 376 at the various sites, were monitored inside the sleeping quarters of the 22 test participants. A total of 4,300 noise events, from as few as 97 to as many as 607, were detected at the outdoor monitoring positions. Mean values of indoor noise event MXFA ranged from 57.6 to 72.2 dB among the various test participants' homes. Outdoor MXFA values varied over the much narrower range of 75.3 to 77.1 dB. The differences in ranges of maximum noise event levels indoors and outdoors reflect differences between interior noise sources in different homes on the one hand, and the common (aircraft) outdoor noise sources on the other.

#### **4.2.2 Noise Environment During Olympics**

Table 16 in Appendix B summarizes the noise environment during the Olympics (17 July through 4 August 1996). Noise events recorded inside participants' sleeping quarters ranged from 5 to 241 among the 12 monitoring sites, for a total of 737. A total of 5,561 noise events were detected outdoors, ranging from 72 to 920 among the 12 monitoring sites. Mean values of indoor noise event MXFA ranged from 57.1 to 74.2 dB among the various test participants' homes. Average outdoor MXFA values ranged from 74.1 to 76.6 dB.

#### **4.2.3 Noise Environment After Olympics**

Table 17 in Appendix B summarizes the noise environment for the data collection period after the end of the Olympics (5-11 August 1996). The number of noise events as defined in Section 2.2.1 of Fidell *et al.* (1995b) recorded inside participants' sleeping quarters ranged from 2 to 250 at 12 monitoring sites, for a total of 508. A total of 1,432 noise events were estimated outdoors, varying in number from 29 to 261 for the 12 homes. Mean values of indoor noise event MXFA ranged from 57.5 to 82.1 dB among the various test participants' homes. Average outdoor MXFA values varied from 72.4 to 80 dB.

#### **4.2.4 Relationship Between Indoor and Outdoor Noise Levels**

Tables 15, 16 and 17 in Appendix B show much greater variability of indoor noise event levels than of events recorded outdoors. This difference in variability also is evident for TAVA evaluated for the 621 subject-nights for which both indoor and outdoor noise levels were available. Outdoor noise levels were found to be reliably less variable ( $SD = 4.69$ ) than were indoor noise levels ( $SD = 10.02$ ),  $F(620, 620) = 4.56$ ,  $p < .001$ . No statistically reliable relationship was found between indoor and outdoor nighttime TAVA for the 621 subject-nights for which it was possible to directly compare the two sets of noise levels ( $p = .12$ ).

### **4.3 DESCRIPTION OF SLEEP DISTURBANCE OBSERVATIONS**

Table 4 summarizes the number of awakenings confirmed by button pushes.

#### **4.3.1 Observations Before Olympics**

A total of 294 subject-nights of analyzable data was collected from 22 test participants living in 12 homes near PDK from 29 June to 16 July 1996.<sup>6</sup> Five hundred and forty behavioral awakening responses (button pushes) were recorded during the 294 subject-nights, for an average of about 1.8 per night.

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<sup>6</sup> Numbers of participants may not sum to the totals seen in Table 2 because data that did not meet quality control standards were omitted from this and further analyses.

**Table 4**  
nights.

Summary of behavioral awakening responses for all subject-

| TIME FRAME                | VARIABLE  |  |  |
|---------------------------|---|--|--|
|                           | Average number of behaviorally-confirmed awakenings per night | Average number of spontaneous awakenings per night | Average number of noise-related awakenings per night |
| Before and after Olympics |   |  |  |
| Mean                      | 1.63  | 1.20   | 0.43   |
| Standard deviation        | 1.73  | 1.45   | 0.89   |
| Range                     | 0-10  | 0-8  | 0-7  |
| During Olympics           |   |  |  |
| Mean                      | 1.25  | 0.83   | 0.42   |
| Standard deviation        | 1.40  | 1.05   | 0.86   |
| Range                     | 0-6   | 0-6  | 0-5  |
| Average over all nights   |   |  |  |
| Mean                      | 1.47  | 1.05   | 0.42   |
| Standard deviation        | 1.61  | 1.31   | 0.88   |
| Range                     | 0-10  | 0-8  | 0-7  |

Participants' answers to the evening and morning questionnaire items in this data set (*cf.* Figures 24 through 29 in Appendix C) indicated that they felt very or extremely tired during the day 29% of the time. Self-reports of number of awakenings averaged 2.05 per night. Responses on 27% of the nights indicated that participants slept well or extremely well during the night. Responses on 63% of the nights indicated that test participants fell asleep within 20 minutes of retiring. For 65% of the nights, participants recalled being awake less than 20 minutes during the night. Reports of high annoyance due to nighttime noise were made on about 2% of the subject-nights.

### 4.3.2 Observations During Olympics

The same 22 participants living in 12 homes provided data for this round of observations. A total of 370 behavioral awakening responses was logged during 295 subject-nights, for an average of 1.3 per night.

Participants' answers to questionnaire items for the entire set of measurement nights (*cf.* Figures 24 through 29 in Appendix C) indicated that they felt very or extremely tired during the day 31% of the time, and that they slept well or extremely well on 27% of the nights. Self-reports of number of awakenings averaged 1.59 per night. Responses on 70% of the nights indicated that test participants fell asleep within 20 minutes of retiring. For 67% of the nights, participants recalled being awake less than 20 minutes during the night. Reports of high annoyance due to nighttime noise were made on about 2% of the subject-nights.

**Table 5** Description of data sets analyzed.

| DEFINITION OF CASE   | DATA SET ANALYZED              | NUMBER OF CASES |                 |                |
|--|--------------------------------|-----------------|-----------------|----------------|
|  |                                | Before Olympics | During Olympics | After Olympics |
| Single subject-night of data   | Whole night                    | 294             | 295             | 97             |
| Single behavioral awakening as defined by a button push  | Behavioral awakening responses | 540             | 370             | 98             |
| Noise event exceeding fixed indoor or outdoor noise level threshold occurring during individual test participant sleep times between 2200 and 0700 hours | Subject-specific noise events  | 2,469           | 3,381           | 930            |
|  | Monitored indoors              | 655             | 486             | 346            |
|  | Monitored outdoors             | 1,814           | 2,895           | 584            |

### 4.3.3 Observations After Olympics

The same 22 participants contributed data to the last round of collection. A total of 98 behavioral awakening responses was logged in the 97 nights of data collection, for an average of one per night.

Participants' answers to questionnaire items for the entire set of measurement nights (*cf.* Figures 24 through 29 in Appendix C) indicated that they felt very or extremely tired during the day 24% of the time and slept well or extremely well 26% of the nights. Self-reports of number of awakenings averaged 1.61 times per night. Responses on 71% of the nights indicated that test participants fell asleep within 20 minutes of retiring. For 66% of the nights, participants recalled being awake less than 20 minutes during the night. Reports of high annoyance due to nighttime noise were made on about 2% of the subject-nights.

## 4.4 INFERENCE ANALYSES

Pre-planned analyses were conducted on three data sets developed for each round of observations, as shown in Table 5:

1. Whole nights (each case is a single subject-night of data);
2. Behavioral awakening responses (each case is an individual button push); and
3. Subject-specific noise events (each case is a noise event occurring during the sleep times of a single test participant between 2200 and 0700 hours, defined by either indoor or outdoor criteria).

### 4.4.1 Dosage-Response Relationships

All dosage-response relationships were constructed from noise event data collected between 2200 and 0700 hours, since earlier time periods in the evening and later time periods in the morning contained too high a density of noise events for reliable association with individual responses.

Dosage-response relationships were constructed for three indicators of sleep disturbance:

1. Behavioral awakening responses (button pushes);
2. Motility as recorded actimetrically; and
3. Arousals as defined by Cole *et al.* (1992)<sup>7</sup> criterion for the actimetric data.

The independent (predictor) variable for all dosage-response relationships was either indoor or outdoor SEL, quantized in 3 dB intervals. Data points reflect the proportion of noise events in each noise level interval that could be associated with a response. Data were combined for all test participants and all data collection sessions for behavioral awakening and actimeter responses. Table 6 shows the definitions of awakening, arousal, and motility adopted for the various data collection

**Table 6** Definitions of awakening, arousal and motility adopted for various data collection devices.

| INDICATION OF SLEEP DISTURBANCE | RECORDING DEVICE | CRITERION OF EFFECT   |
|---------------------------------|------------------|---|
| Awakening                       | Push button      | Occurrence of response within five minutes of start of noise event                      |
| Arousal                         | Actimeter        | As defined by Cole <i>et al.</i> (1992) using base algorithm without iteration          |
| Motility                        | Actimeter        | Any activity occurring in any of the ten 30-sec epochs after the start of a noise event |

devices.

One-sided analyses of significance of associations of sleep disturbance and noise events were tested at  $\alpha = .025$ . This seemingly lax criterion was adopted because of the relatively low power associated with the sample sizes generated by the 3-dB-wide SEL categories — in the neighborhood of  $N = 10$  to  $12$ . At this level of significance, a correlation coefficient of about .53 to .58 is required for statistical reliability. Any 3 dB interval containing fewer than 15 noise events was excluded from analysis.

Correlations for the various dosage-response relationships are summarized in Table 7. Two of the six dosage response relationships were statistically reliable. The SEL value of indoor noise events successfully predicted arousals as defined by Cole *et al.* (1992), and the SEL value of outdoor noise events successfully predicted behavioral awakenings as confirmed by button pushes.

Figure 8 shows that indoor SEL of noise events predicted arousal moderately well,  $r(8) = .64$ ,  $p = .022$ . The probability of arousal increased by about 5% with each 10 dB increase in SEL. Polynomial regression failed to reveal any statistically reliable quadratic relationship.

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<sup>7</sup> Cole, Kripke, Gruen, Mullaney, and Gillin, 1992.

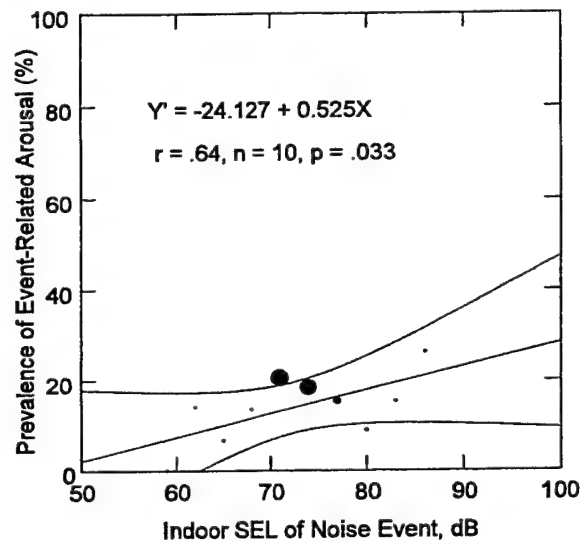
**Table 7**

Summary of dosage-response correlations for events occurring between 2200 and 0700 hours (data aggregated over all nights).

| MEASURE OF SLEEP DISTURBANCE | CRITERION FOR SLEEP DISTURBANCE | NUMBER OF INDOOR NOISE EVENTS | NUMBER OF OUTDOOR NOISE EVENTS | NOISE MEASUREMENT TYPE |                   |
|------------------------------|---------------------------------|-------------------------------|--------------------------------|------------------------|-------------------|
|                              |                                 |                               |                                | Indoor Criterion       | Outdoor Criterion |
| Motility                     | Actimetric zero crossings       | 1,487                         | 5,293                          | NS                     | NS                |
| Arousal                      | Cole <i>et al.</i> (1992)       | 1,329                         | 4,693                          | .64 *                  | NS                |
| Awakening                    | Behavioral awakening response   | 1,487                         | 5,293                          | NS                     | .77 *             |

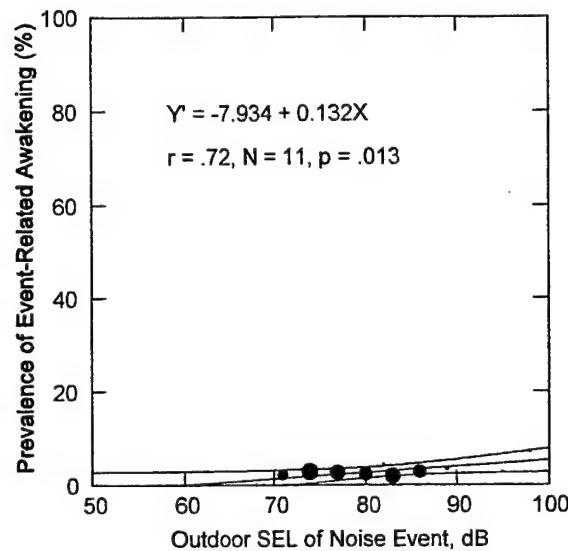
\*  $p < .025$ , one-sided test

NS: Not significantly different from a correlation of 0

**Figure 8**

Prevalence of arousal aggregated by test participants in 3 dB intervals of indoor noise measurements. Curved lines bound the 95% confidence interval. Larger data points indicate relatively greater numbers of events.

Figure 9 shows that the outdoor SEL of noise events predicted behavioral awakening responses fairly well,  $r(9) = .72$ ,  $p = .013$ . The probability of awakening increased by about 1.3% with each 10 dB increase in SEL. Polynomial regression revealed no statistically reliable quadratic relationship.



**Figure 9** Prevalence of behavioral awakening responses aggregated by test participants in 3 dB intervals of outdoor noise measurements. Curved lines bound the 95% confidence interval. Larger data points indicate relatively greater numbers of events.

#### 4.4.2 Temporal Adaptation of Behaviorally-Defined Awakenings and Self-Reported Sleep Latency

Eleven test participants living near PDK provided analyzable data for the three test periods: immediately before, during, and immediately after the 1996 Olympics. Analyses of temporal effects in this data set were based on whole night data, ignoring the first three nights of data collection as a period of familiarization with the in-home instrumentation. The entire data collection period was divided into seven sequential intervals for purposes of this analysis:

1. Several nights of data collection (following the first three nights for each participant) prior to two nights before the start of the Olympics (2-14 July);
2. The two nights before the start of the Olympics (15 and 16 July);
3. The first two nights after the start of the Olympics (17 and 18 July);
4. Mid-Olympic nights (19 July to 2 August);
5. The last two nights of the Olympics (3 and 4 August);
6. The first two nights after the end of the Olympics (5 and 6 August); and
7. The remaining nights of data collection (7-11 August).

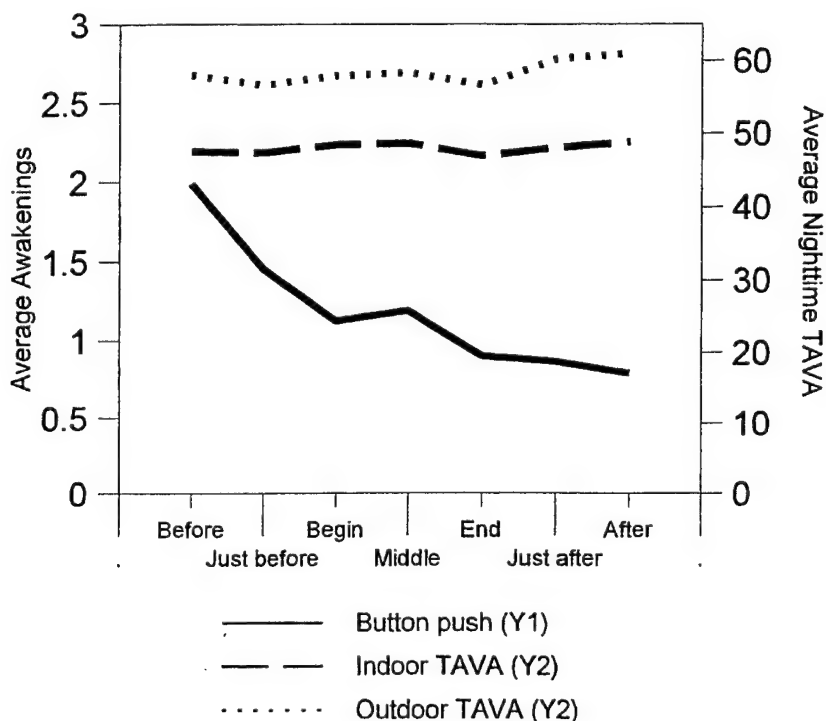
Plots of behavioral awakening responses on successive nights for each participant may be found in Appendix D.

A profile analysis of repeated measures of behavioral awakening responses and recalled time

to fall asleep as dependent variables, after adjustment for total time slept as a covariate, showed a significant relationship with time period, the independent variable, multivariate  $F(12, 114) = 2.36$ ,  $p < .05$ . Sequential interval accounted for 20% of the variability in the combination of sleep disruption measures. A step-down analysis was performed on the two sleep disruption variables, in which the test for time to fall asleep was adjusted for awakenings recorded by button pushes as well as time slept, but the test for behavioral awakening responses was adjusted only for time slept. In other words, behavioral awakening responses were assigned greater importance as a sleep disruption measure than was recalled latency to fall asleep. Each test was done with a probability of Type I ( $\alpha$ ) error set at .025. By this criterion, neither of the measures reached statistical reliability individually. A parallel analysis was performed separately on motility (for which only nine respondents provided usable data) but showed no difference in responses over the time periods.

Figure 10 shows the average number of behavioral awakening responses as a function of time period, as well as the indoor and outdoor TAVA for those time periods. A planned contrast revealed no significant difference in average number of behavioral awakening responses before and after the Olympics as contrasted with responses during the Olympics,  $p > .025$ . However, a planned trend analysis revealed that the apparent negative linear trend of Figure 10 was statistically significant,  $F(1, 9) = 9.18$ ,  $p < .025$ .

The apparent *positive* linear trend of outdoor TAVA over the seven time periods was statistically reliable,  $F(1, 10) = 11.65$ ,  $p < .025$ , as was the quadratic trend,  $F(1, 10) = 12.83$ ,  $p < .025$ .



**Figure 10** Behavioral awakening responses, indoor TAVA, and outdoor TAVA during intervals before, during, and after Olympic games.

.025. Small but statistically reliable difference in outdoor TAVA between nights recorded during the Olympics (mean = 58 dB), and the combination of nights before and after the Olympics (mean = 59 dB),  $F(1, 10) = 45.23$ ,  $p < .025$ , were also observed. No reliable difference in indoor TAVA was found over the seven time periods, nor was a reliable association found between behavioral awakening and either indoor or outdoor sound levels.

#### 4.4.3 Relationships Among Sleep Disturbance Measures

##### 4.4.3.1 Awakening and arousal

A two-way frequency analysis explored the relationship behavioral awakenings and arousal using the actimetric criterion of Cole *et al.* (1992). This analysis was based on a total of 4,693 noise events measured outdoors. Outdoor noise events were chosen for analysis because of their greater number. Table 8 shows the distribution of noise events.

**Table 8** Cross-tabulation of numbers of outdoor noise events ( $N = 4,693$ ) associated with arousal and with behaviorally confirmed awakening.

| ACTIMETER<br>AROUSAL | BUTTON PUSH |        |
|----------------------|-------------|--------|
|                      | Present     | Absent |
| Yes                  | 68          | 576    |
| No                   | 65          | 3,984  |

The relationship between behavioral awakening responses and the actimetric criterion for arousals,  $\chi^2(1) = 161.76$ ,  $p < .001$ ,  $\phi^2 = .03$ , indicated that about half (51%) of the noise events producing behavioral awakening responses also produced arousals by the actimetric criterion, but only 13% of the noise events without behavioral awakening responses produced enough response in the actimeter to be recorded as an arousal.

##### 4.4.3.2 Awakening and motility

Relationships between behavioral awakening responses and motility were also explored through a two-way analysis of the 4,693 noise events recorded outdoors. Table 9 shows the distribution of noise events.

**Table 9** Cross-tabulation of numbers of outdoor noise events (N = 4,693) associated with awakenings and motility.

| MOTILITY | BUTTON PUSH |        |
|----------|-------------|--------|
|          | Present     | Absent |
| Yes      | 126         | 3,326  |
| No       | 7           | 1,234  |

Actimetric motility (zero crossings in 30-second epochs) reliably predicted awakenings. The relationship between behavioral awakening responses and at least one actimetric threshold crossing,  $\chi^2(1) = 31.57, p < .001, \phi^2 = .01$ , indicated that while almost all (95%) of the noise events that produced a button push also were followed by an actimetric indication of motility, almost three-quarters of the noise events (73%) not associated with a button push were also followed by an actimetric response.

#### **4.4.3.3 Behavioral and recalled awakening**

The relationship between behavioral awakening responses and the time spent awake (as recalled the following morning) was assessed using the all-night data. Median recalled time awake was between 10 and 20 minutes, while median number of behaviorally-confirmed awakenings was 1. After applying a logarithmic transform to compensate for positive skewness in recalled time awake and a square root transform to compensate for positive skewness in behaviorally-confirmed awakenings, a moderate linear relationship was found between them,  $r(683) = .52, p < .001$ .

#### **4.4.4 Predicting Sleep Disturbance from Noise Level and Control Variables**

Direct logistic regression analysis was employed to predict sleep disturbance following noise events from the levels of the noise events, ambient noise levels, personal characteristics of respondents, time-related characteristics, and rating of tiredness the previous evening. Logistic regression is an appropriate analytic tool when the predicted variable represents the probability of an outcome (in this case whether sleep is disturbed) and when predictor variables are a mixture of discrete and continuous measures (Tabachnick and Fidell, 1996).

Noise events analyzed were those occurring between 2200 and 0700 hours. Each event constituted a case for analysis. The measures of sleep disturbance were the two that showed a statistically significant dosage-response relationship: behavioral awakening responses with noise measured outdoors, and arousal responses with noise measured indoors. Type I error rate was controlled by setting  $\alpha = .005$  for each predictor. Contribution of each predictor variable is assessed after controlling for all other predictor variables in direct logistic regression.

Predictors included two sound level measures: SEL of noise events and TAVA of ambient level in sleeping quarters. Personal characteristics included gender, the linear effect of years of age,

the quadratic effect of age (in which younger and older participants were combined and compared with participants 35-49 years of age), and spontaneous (non-event related) numbers of awakenings for the night in which the event occurred. Because the latter measure was poorly distributed, it was transformed by taking the inverse of spontaneous number of awakenings + 1, and then the measure was reflected (*i.e.*, the analyzed measure was 1 minus the inverse) to correspond with the direction of the original measure.

Time-related characteristics were time since retiring in 15-min intervals, duration of residence in months, and study duration as indicated by number of nights in the study when the event occurred. A final predictor was a rating of tiredness during the previous day on a scale of 1-5, in which 1 indicated not at all tired and 5 indicated extremely tired.

Table 10 summarizes the results of the logistic regression analyses. Noise events considered were those for which data were available for all 10 predictors and the sleep disturbance measure of interest.

**Table 10** Summary of logistic regression analyses of behavioral awakenings and arousals by SEL of individual events and additional predictors.

| CHARACTERISTIC   | BEHAVIORAL AWAKENING (NOISE MEASURED OUTDOORS) | AROUSAL (NOISE MEASURED INDOORS)         |
|--|--|--|
| Number of events with disturbance / total events                                   | 132 / 5,071                                    | 192 / 1,174                              |
| Significant predictors (each adjusted for all others)                              | Night, spontaneous awakenings                  | Night, spontaneous awakenings, tiredness |
| Full model (10 predictors)<br>Variance accounted for<br>Prediction success<br>$d'$ | 4%<br>95%<br>0.63                              | 5%<br>74%<br>0.64                        |
| SEL alone<br>Variance accounted for<br>Prediction success<br>$d'$                  | NS<br>NS<br>NS                                 | NS<br>NS<br>NS                           |
| Average outdoor SEL that did/did not disturb sleep                                 | NS   | NS                                       |

NS: Not statistically significant at  $\alpha = .005$

#### 4.4.4.1 Prediction of behavioral awakening (outdoor noise measurements)

Data for the analysis were provided by all 22 participants, responding to a total of 5,071 noise events recorded outdoors between 2200 and 0700 hours.

The combination of 10 variables reliably predicted awakening as recorded by behavioral awakening responses, with a model produced by those variables better than a chance model,  $\chi^2(10) = 49.11, p < .001$ . Two variables significantly added to the remaining variables in prediction of awakening: spontaneous awakening rate and study duration, as seen in Table 18 of Appendix E. Spontaneous awakening rate (after inverting and reflecting to compensate for severe skewness) was associated with behavioral awakening; the greater the spontaneous rate of awakening, the greater the

likelihood of awakening in the presence of a noise event. Probability of awakening decreased by about 3% with each subsequent night in the study. SEL did not reliably predict behavioral awakening in the presence of other predictors in this analysis.

The prediction success rate of 95% for the full model reflects the extreme rarity of noise events that elicited behavioral awakening responses: 132 out of 5,071. Using McFadden's  $\rho^2$  criterion, the model accounted for 4% of the variance in awakening. A model based solely on SEL of noise events failed to predict awakening better than a chance model ( $p > .005$ ).

The ROC analysis of awakening as signaled by behavioral awakening responses yielded a  $d'$  value of 0.63 for the receiver operating characteristic curve of the model with all 10 predictors.

#### **4.4.4.2 Prediction of arousals (indoor noise measurements)**

Data for the analysis were provided by all 22 participants, responding to a total of 1,174 noise events recorded outdoors, occurring between 2200 and 0700 hours.

The combination of 10 variables reliably predicted arousals by Cole *et al.*'s (1992) actimetric criterion, with a model produced by those variables better than a chance model,  $\chi^2(10) = 51.18$ ,  $p < .001$ . Three variables significantly added to the remaining variables in prediction of arousal: spontaneous awakening rate, tiredness and study duration, as seen in Table 19 of Appendix E. Spontaneous awakening rate (after inverting and reflecting to compensate for severe skewness) was *negatively* associated with arousals; the lower the spontaneous rate of awakening, the greater the likelihood of arousal in the presence of a noise event. Probability of arousals increased by about 50% with each 1-unit increase in rating of recalled tiredness the previous day. Probability of arousal *increased* by about 2% with each subsequent night in the study. SEL did not reliably predict behavioral awakening in the presence of other predictors in this analysis.

The prediction success rate of 74% for the full model reflects the rarity of noise events that elicited arousal responses: 192 out of 1,174. Using McFadden's  $\rho^2$  criterion, the model accounted for 5% of the variance in arousal. A model based solely on SEL of noise events failed to predict arousal better than a chance model ( $p > .005$ ).

The ROC analysis of arousal as signaled by Cole *et al.*'s (1992) actimetric criterion yielded a  $d'$  value of 0.64 for the receiver operating characteristic curve of the model with all 10 predictors.

## 5 RESULTS OF MOTILITY MEASUREMENTS

This chapter describes analyses of motility measurements in epochs of varying durations. Table 11 accounts for observation periods of different test participants in various sleeping quarters. The analyses reported in this chapter start by characterizing the motility observations on a nightly basis as quantified in epochs of varying duration. The next set of analyses focuses on general sequential dependence in motility measurements, and then on characterization of motility measurements in consecutive epochs ("runs") with and without movement. Information about noise levels in sleeping quarters is presented next, followed by an analysis of relationships between noise levels and runs with and without movement.

**Table 11** Numbers of nights of analyzable motility data collected in 2 second epochs during all rounds of data collection.

| TEST<br>SUBJECT<br>NUMBER | NUMBER OF NIGHTS IN STUDY AT EACH DATA<br>COLLECTION SITE |                                 |                  | TOTAL<br>NUMBER OF<br>NIGHTS IN<br>STUDY |
|---------------------------|---|---------------------------------|------------------|--|
|                           | Los Angeles<br>International Airport                      | Unfamiliar<br>Sleeping Quarters | Suburban<br>Site |  |
| 1                         | 5   |                                 |                  | 5  |
| 2                         | 3   |                                 |                  | 3  |
| 3                         | 4   |                                 |                  | 4  |
| 4                         | 5   |                                 |                  | 5  |
| 5                         | 4   |                                 |                  | 4  |
| 6                         | 5   |                                 |                  | 5  |
| 7                         | 4   |                                 |                  | 4  |
| 8                         | 4   |                                 |                  | 4  |
| 9                         | 4   |                                 |                  | 4  |
| 10                        | 5   |                                 |                  | 5  |
| 11                        |   | 2                               |                  | 2  |
| 12                        |   | 8                               | 5                | 13                                       |
| 13                        |   | 9                               |                  | 9  |
| 14                        |   | 2                               | 5                | 7  |
| 15                        |   | 2                               | 5                | 7  |
| 16                        |   | 1                               |                  | 1  |
| 17                        |   | 3                               | 3                | 6  |
| 18                        |   | 2                               |                  | 2  |
| 19                        |   |                                 | 5                | 5  |
| 20                        |   |                                 | 6                | 6  |
| 21                        |   |                                 | 3                | 3  |
| 22                        |   |                                 | 5                | 5  |
| Total                     | 43  | 29                              | 37               | 109                                      |

## 5.1 DATA PROCESSING

Digital files containing numbers of zero crossings in successive 2-second actigraph periods were combined to create six additional data files with zero crossing values in 4, 6, 8, 10, 20, and 30 second epochs throughout each subject-night. A similar procedure was applied to the 2-second indoor noise exposure data to construct TAVA values in 4, 6, 8, 10, 20, and 30 second epochs.

Since interest in actimetric measurements focused on times when test participants were in bed intending to sleep, actigraph data in 30-second epochs were examined to determine the time of first occurrence of half a dozen or more epochs without movement, as confirmed by subjects' records of time at retiring. Further, a minimum of the last hour of actigraph data was excluded from analysis to ensure that times when subjects were no longer in bed were not treated as sleep time. Illness or failure to wear actigraphs accounted for missing data during 8 of 117 subject-nights.

## 5.2 GROSS CHARACTERIZATION OF MOTILITY IN EPOCHS OF VARYING DURATION

Figure 11 presents a gross summary of motility measurements in epochs of varying duration. The figure displays grand means and standard deviations of zero crossings in epochs ranging from 2 to 30 seconds in duration, calculated on a nightly basis for all test participants at all sites.<sup>8</sup> (On the logarithmically scaled abscissa, a value of 0.3 corresponds to an epoch duration of 2 seconds.) The mean to sigma ratios for the distributions of zero crossings are about 2:1 for all epochs of durations greater than 2 seconds.

The seven panels of Figure 12 show distributions for the entire data set of mean numbers of zero crossings per subject-night in epochs of varying duration. Since direct comparisons across epoch durations are facilitated by standardizing the scale of the abscissa, these data have been normalized to a nominal one second duration. The normalization also emphasizes the constriction of the range of the mean zero crossing values in epochs of shorter duration.

## 5.3 INDIVIDUAL DIFFERENCES IN MOTILITY

Individual differences in motility are depicted in the seven panels of Figure 13 for epochs of 2 through 30 seconds in duration for each test participant's entire data set. Mean numbers of nightly zero crossings per epoch are plotted in Figure 13 as filled points. The largest and smallest values of mean nightly zero crossings are shown as range bars about each test participant's grand mean.<sup>9</sup> It is readily apparent that differences in response rates among test participants are obscured in the

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<sup>8</sup> Mean values are plotted on a logarithmic ordinate to emphasize that the linear trend in numbers of zero crossings per epoch with increasing epoch duration follows from the summing of zero crossing values in shorter epochs. Note that values of the standard deviation are plotted on a linear ordinate.

<sup>9</sup> Absolute maxima and minima (rather than average values) ranged from no zero crossings at all to nearly as many zero crossings as the actimeters were capable of registering within their measurement bandwidth in each epoch duration.

shorter epochs.

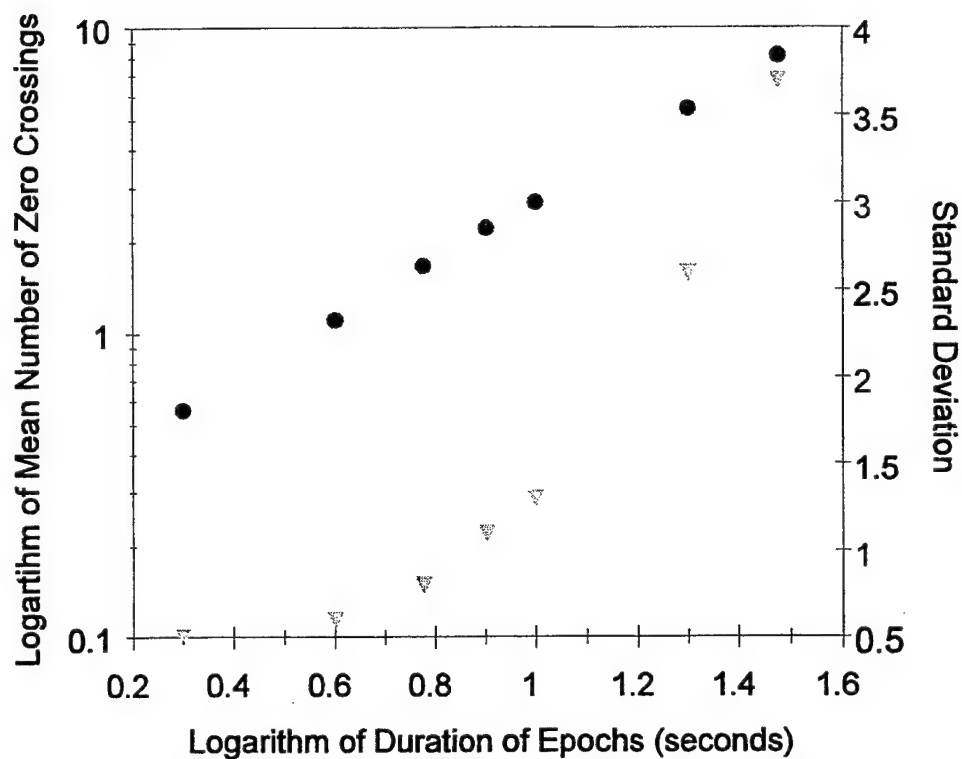
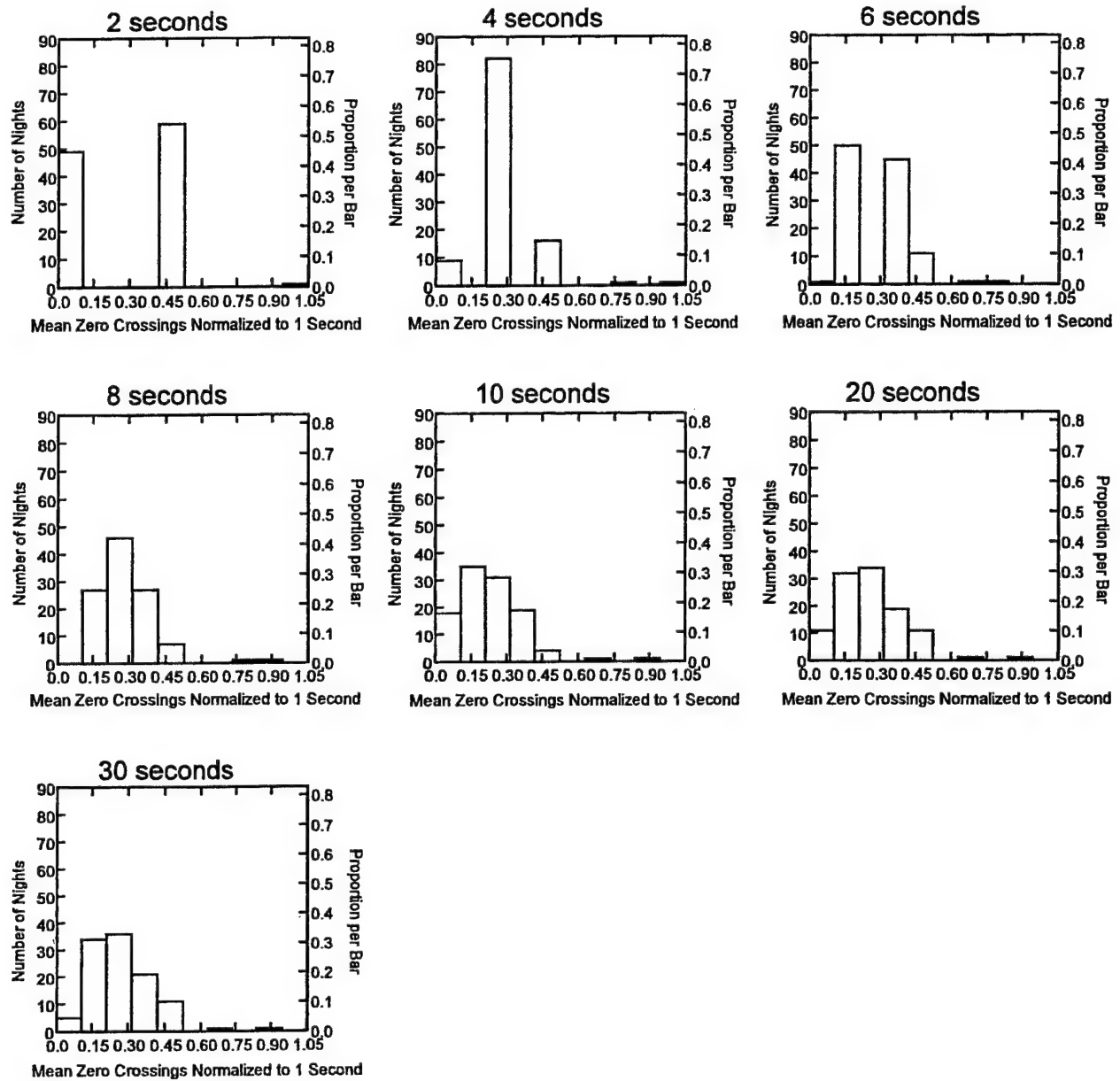
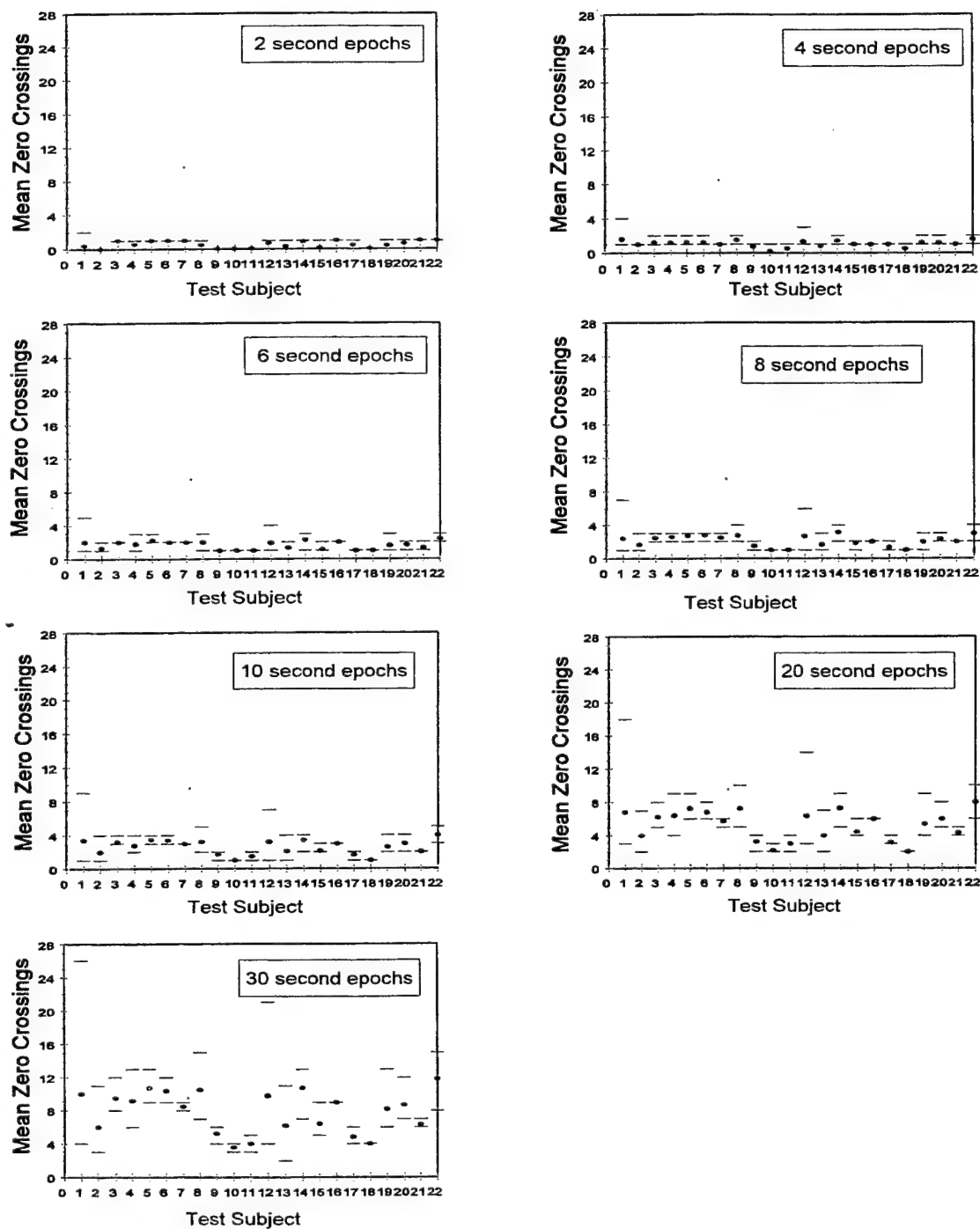


Figure 11

● Mean      ▽ Standard Deviation  
Mean number of zero crossings for entire data set observed in each epoch duration plotted on logarithmic axes. (Standard deviations are plotted on the linear, righthand ordinate.)



**Figure 12** Distribution of mean zero crossing values for each subject-night in epochs of varying duration, normalized to one second.



**Figure 13** Range of individual test participants' mean nightly motility in epochs of varying duration. Filled plotting symbols represent mean numbers of zero crossings. Horizontal lines indicate the smallest and largest values of nightly means.

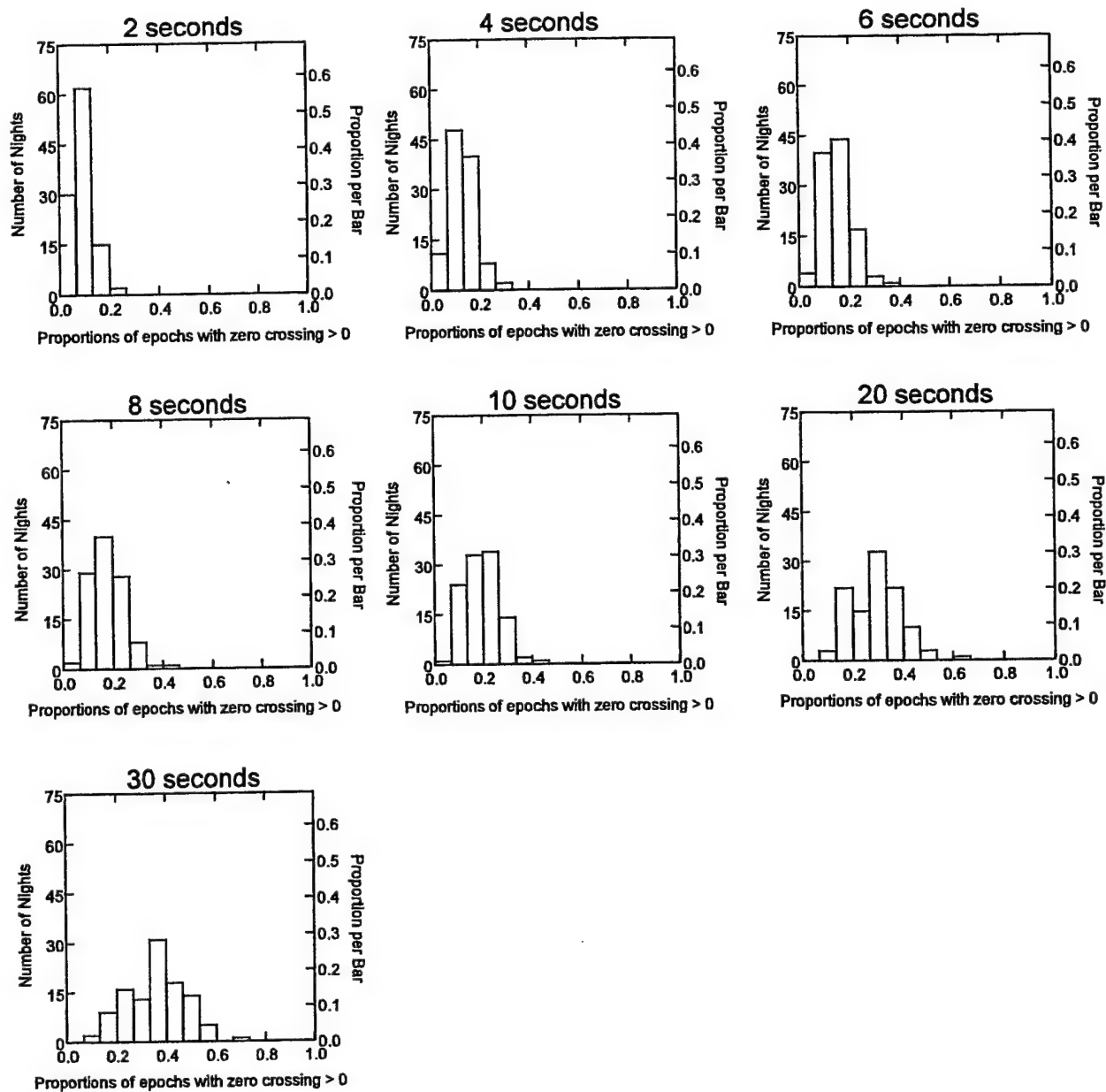
One simple measure of the nightly prevalence of motility is the fraction of all epochs during a subject-night containing at least one zero crossing — or epochs arguably associated with wakefulness. The seven panels of Figure 14 show distributions for the entire data set of the fraction of all epochs during each subject-night containing at least one zero crossing during each subject-night. Relatively few epochs during the night contain movement, particularly within epochs of shorter duration. The more symmetric distributions with greater ranges that are apparent in the epochs of longer duration are more tractable to a variety of statistical analyses. Figure 15 displays distributions for the complementary fraction (epochs lacking any zero crossings and hence arguably associated with sleep) during each subject-night.

## 5.4 AUTOCORRELATION IN MOTILITY DATA

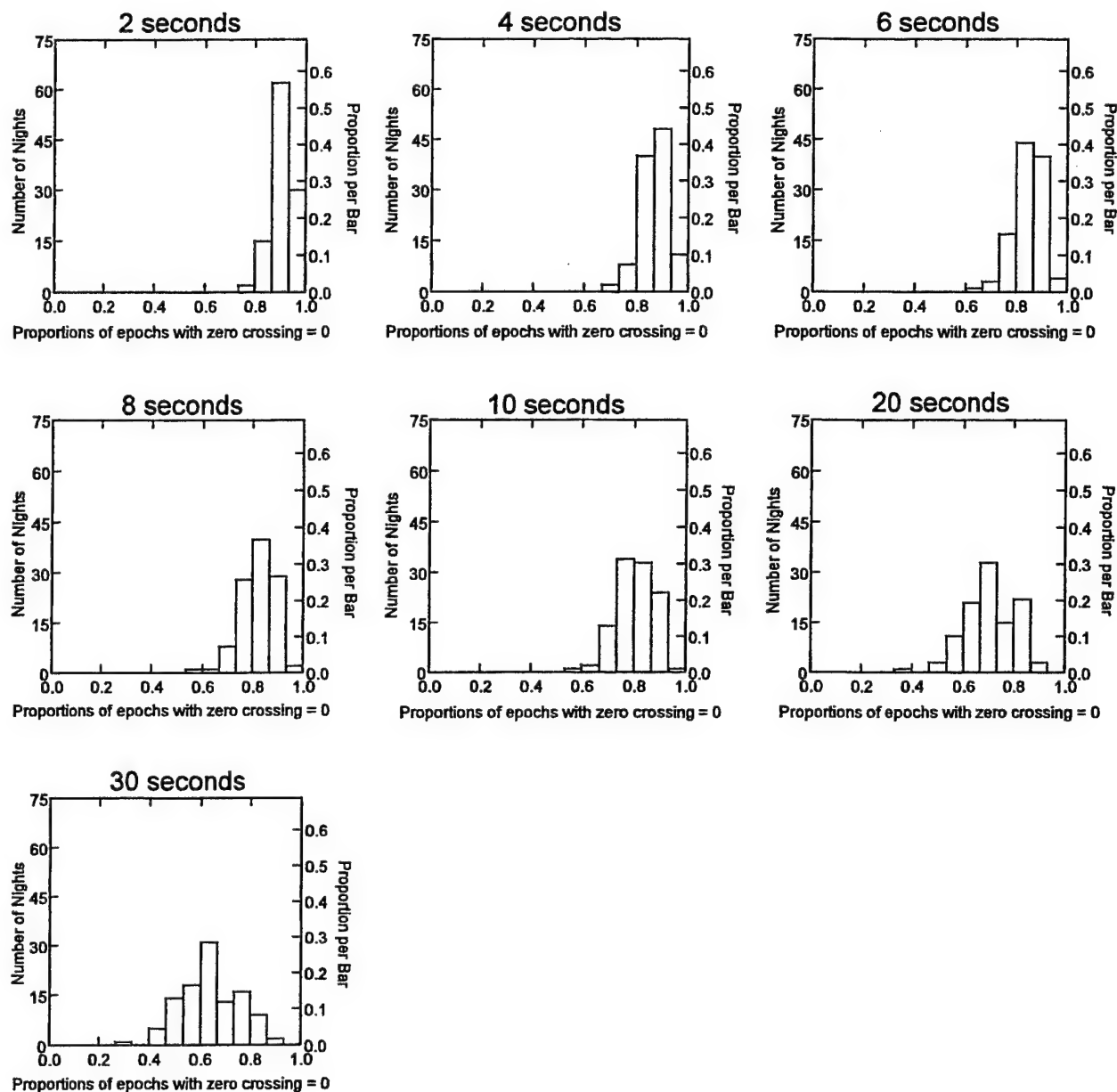
The better established algorithms for inferring sleep and wakefulness from motility measurements (*e.g.*, Cole *et al.*, 1992) are based on patterns of sequential dependencies in successive analysis epochs. The relationship between the occurrence of movement in successive epochs in the present data set was initially examined by autocorrelation techniques. If the occurrence of motility in one epoch predicted nothing about the occurrence of motility in the next, the lack of any serial dependence would suggest that gross body movement occurs at random times and for random durations during the night, without any prolonged temporal linkage to prior causal events such as noise intrusions.

Figure 16 is a typical autocorrelation plot for a single test subject during a single night in epochs of varying duration. The height of the bars indicates the extent of the correlation between zero crossings in epochs successively farther removed in time from the first. Thus, for example, the leftmost bar in each of the panels of Figure 16 shows the correlation between numbers of zero crossings in epochs one epoch apart. The height of the next rightmost bar shows the correlation between numbers of zero crossings in epochs two epochs apart, and so forth.

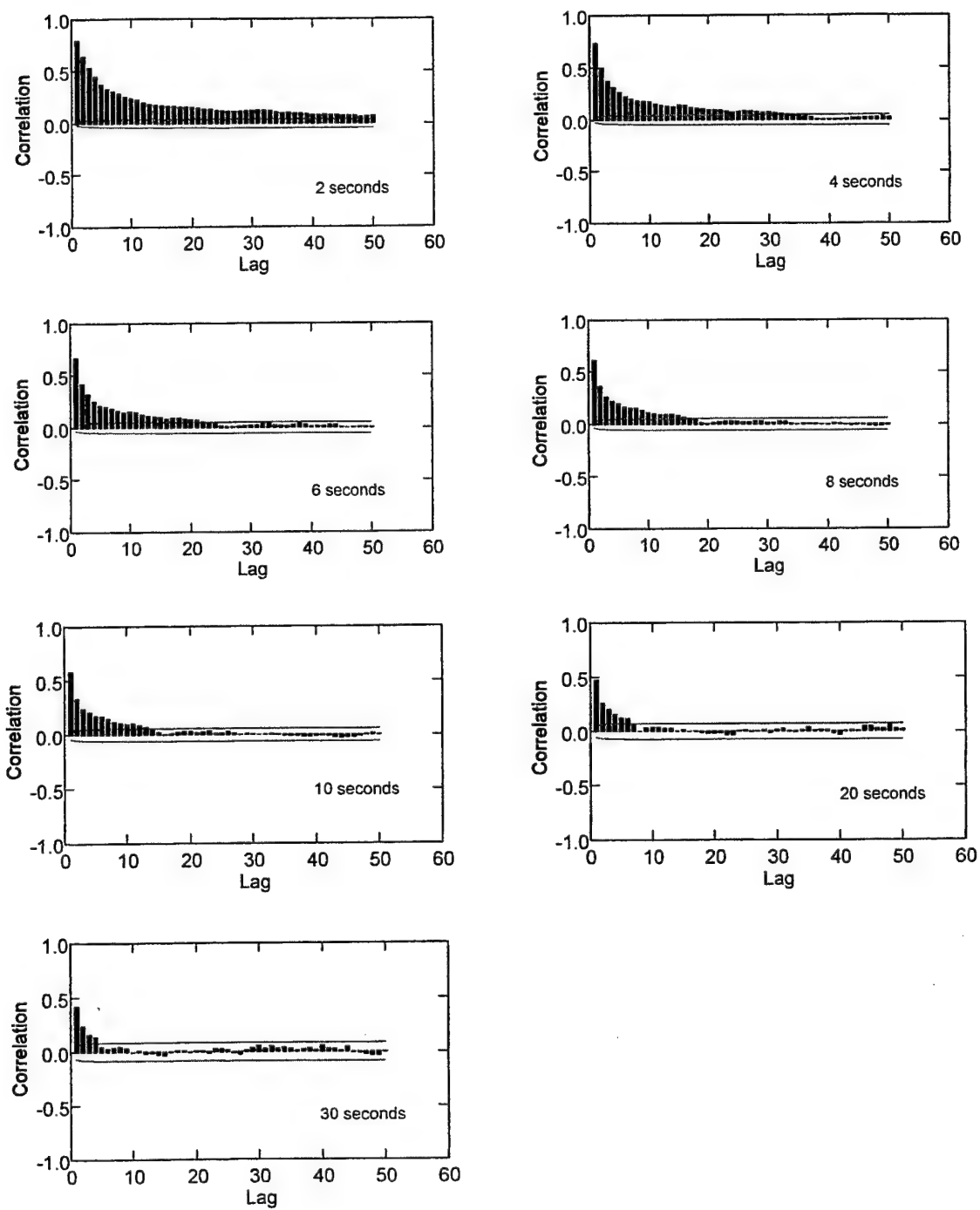
The horizontal lines bound the 95% confidence interval for the significance of correlation values. Any bars that lie within these lines represent correlations that do not differ significantly from zero. Thus, it is apparent from Figure 16 that motility remains correlated for time periods as great as two minutes for this test subject. The exponential decay in correlation values of the sort shown in Figure 16 is typical of a simple autoregressive model lacking periodicity.



**Figure 14** Distribution of proportions of motility epochs (containing at least one zero crossing) for all subject-nights.

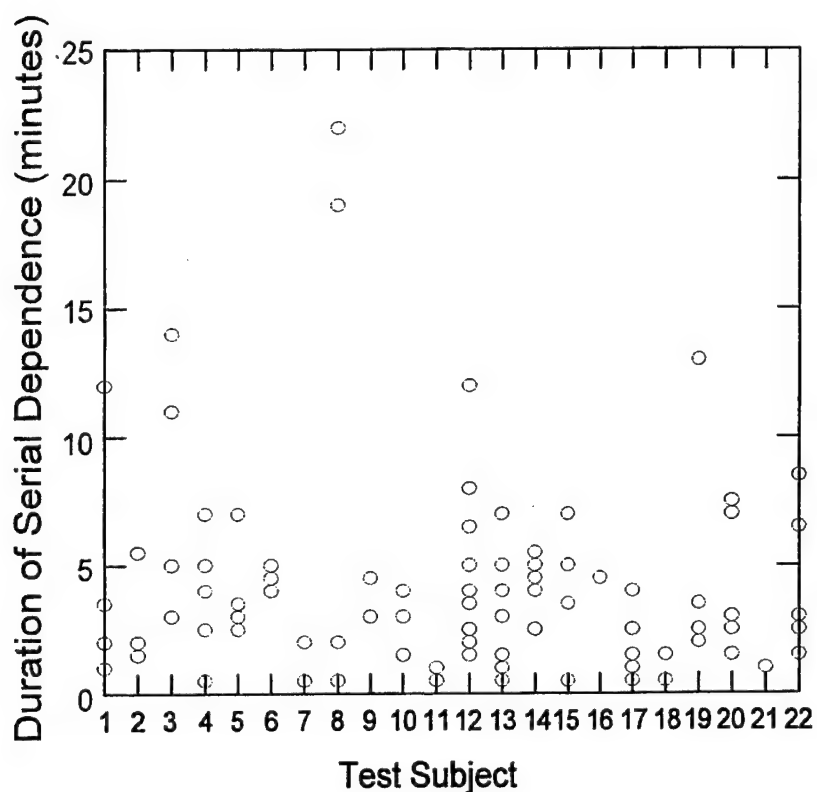


**Figure 15** Distributions of proportions of epochs without movement (zero crossings = 0) for all subject-nights.



**Figure 16** Autocorrelation of motility for a typical subject-night for each epoch duration. The lag plotted on the abscissa indexes time (in units of epochs) between correlated motility measurements.

Figure 17 shows the extent of statistically significant serial dependence (in minutes) observed during each subject-night (plotting symbol) during 30-second epochs. A small percentage of the data points indicate serial dependence over extended time periods, as might be expected during periods of prolonged wakefulness throughout the night. However, the bulk of the motility measurements indicate that significant serial dependence of motility routinely persists for time periods of 5 minutes or less. This in turn suggests that motility measurements probably do not directly reflect nightly cycling through sleep stages on a time scale of tens of minutes or longer.



**Figure 17** Scatter plot of numbers of minutes of serial dependence for all test participants, in 30-second epochs. Each point represents a subject-night.

## 5.5 COMPARISON OF RUNS OF EPOCHS WITH AND WITHOUT MOVEMENT

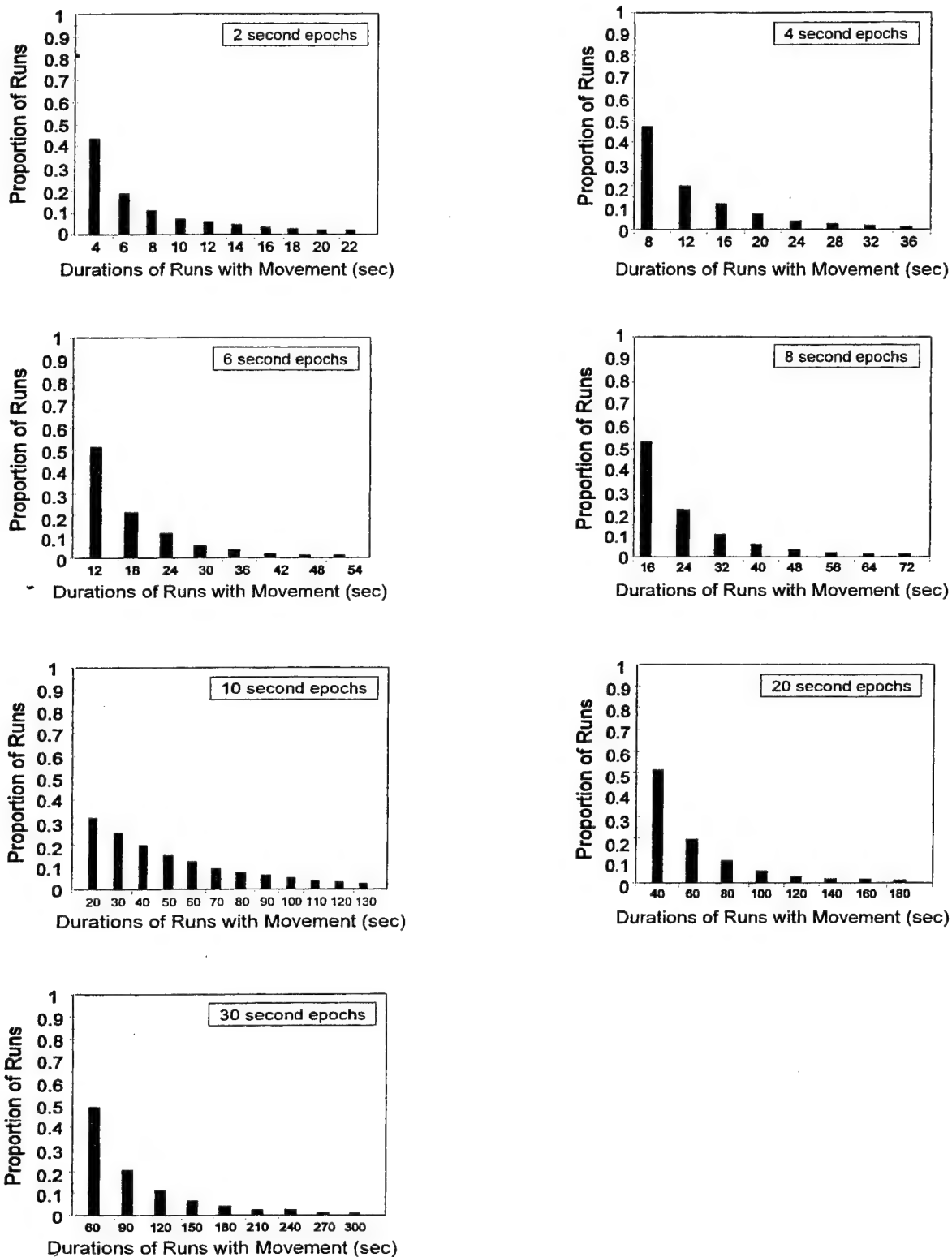
The number of consecutive epochs ("runs") containing movement is another metric useful for comparing gross motility in epochs of varying duration.<sup>10</sup> Runs containing movement were defined as 2 or more consecutive epochs containing zero crossing values greater than zero. The distribution of the number of consecutive epochs containing movement (zero crossings > 0) for all subject-nights may be seen in Figure 18. The abscissa shows the duration of runs containing movement, in seconds. The shortest possible run length in the first panel is 4 seconds (2 epochs in duration), 8 seconds in the second panel, and so forth.

As measured in 2-second epochs, about three quarters of the runs containing movement last for 8 seconds or less. As measured in 4-second epochs, about three quarters of the runs last for 16 seconds or less, and so forth. Since the autocorrelation analyses revealed that motility is temporally correlated over considerably longer periods than these, analyses conducted in shorter duration epochs may underestimate potential effects of external events — such as noise intrusions lasting several epochs — on sleep disturbance as characterized by temporally proximate motility.

Since the shapes of the distributions of runs containing movement are all approximately exponential, they may be summarized and compared quantitatively by a standard exponential curve of the form  $y = e^{-(x+a)/b}$ , where  $x$  is the duration of runs in seconds,  $a$  is a fitting constant, and  $b$  is the mean of the frequency distribution. A minimized residual sum of squares criterion was calculated to serve as a measure of the best fitting function. Table 12 shows the resulting exponential fits to the distributions of runs containing movement in epochs of varying duration, along with correlation coefficients ( $r$ , indicating the goodness of fit) and coefficients of determination ( $r^2$ , indicating the amount of shared variance between durations and numbers of runs). All of the correlation coefficients in Table 12 are statistically different from zero ( $p < .01$ ).

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<sup>10</sup> Run lengths so defined are not necessarily predictable from epoch duration alone. For example, a run of length = 2 in consecutive four-second epochs, each containing movement, does not necessarily imply a run of length = 4 in time-synchronous two-second epochs, all containing movement. An eight-second-long run of two consecutive four-second epochs can be constructed from five temporally distinct patterns of movement and non-movement within four two-second epochs.



**Figure 18** Distributions of run durations with motility in epochs of varying duration.

**Table 12** Exponential fits to the distributions of runs with and without motility.

| DURATION OF EPOCH (SECONDS) | RUNS CONTAINING MOVEMENT |      |                | RUNS LACKING MOVEMENT |      |                |
|-----------------------------|--------------------------|------|----------------|-----------------------|------|----------------|
|                             | Equation                 | r    | r <sup>2</sup> | Equation              | r    | r <sup>2</sup> |
| 2                           | $e^{-(x+10)/10}$         | 0.54 | 0.29           | $e^{-(x+222)/68}$     | 0.68 | 0.46           |
| 4                           | $e^{-(x+11)/16}$         | 0.61 | 0.37           | $e^{-(x+214)/80}$     | 0.71 | 0.50           |
| 6                           | $e^{-(x+16)/24}$         | 0.85 | 0.72           | $e^{-(x+215)/90}$     | 0.91 | 0.83           |
| 8                           | $e^{-(x+21)/32}$         | 0.66 | 0.43           | $e^{-(x+226)/104}$    | 0.75 | 0.56           |
| 10                          | $e^{-(x+26)/40}$         | 0.86 | 0.74           | $e^{-(x+236)/110}$    | 0.92 | 0.84           |
| 20                          | $e^{-(x+54)/80}$         | 0.91 | 0.82           | $e^{-(x+266)/160}$    | 0.93 | 0.87           |
| 30                          | $e^{-(x+86)/120}$        | 0.89 | 0.79           | $e^{-(x+311)/210}$    | 0.94 | 0.88           |

## 5.6 SUMMARY OF NOISE ENVIRONMENTS

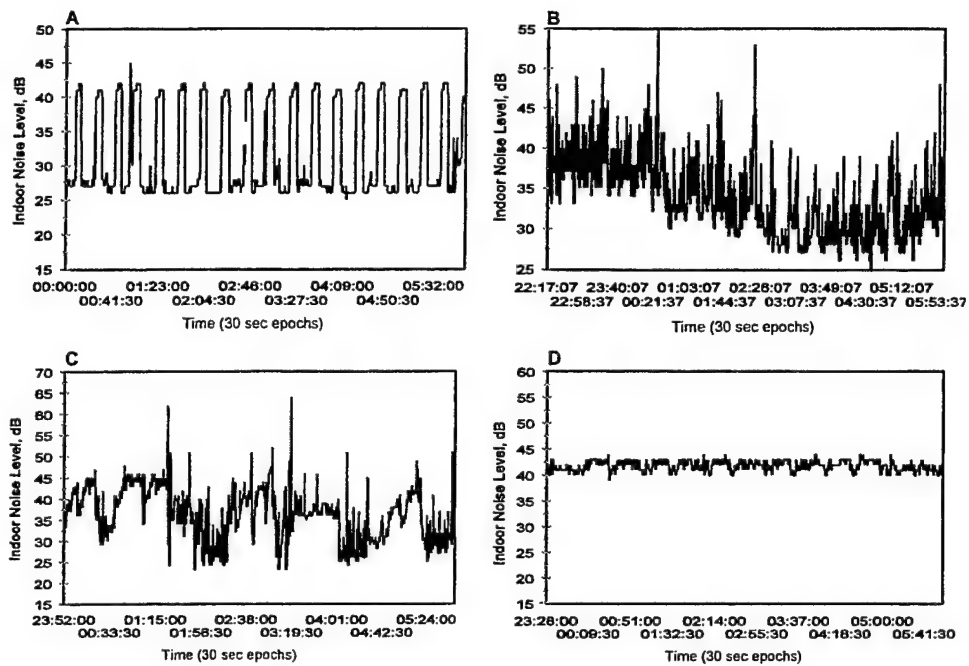
Figure 19 displays four time plots of indoor noise environments (in 30-second intervals) of test participants' sleeping quarters. Although these time plots show obvious differences in temporal patterns and levels of noise within sleeping quarters, none includes large numbers of high level noise intrusions. The periodic structure of the nighttime noise apparent in panel A of Figure 19 was produced by cycling of a thermostatically-controlled heating system. The noise events in the range of  $L_{eq} = 60$  to 65 dB in panel C of the figure were produced by a noisy infant.

## 5.7 INDOOR NOISE LEVELS PRIOR TO THE START OF RUNS WITH AND WITHOUT MOVEMENT

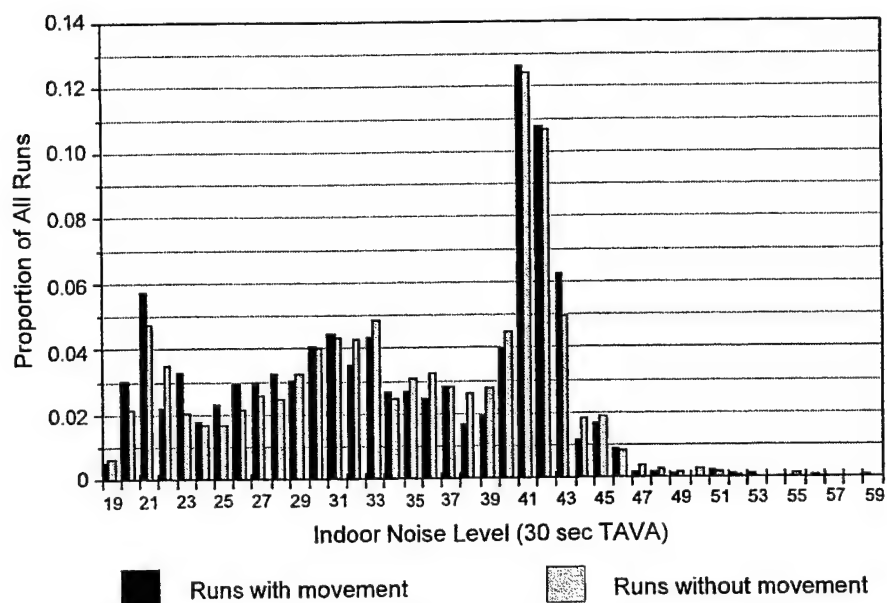
Noise levels in the epoch prior to the start of runs containing movement and runs lacking movement are summarized in Figure 20. No meaningful differences are apparent in the distributions of noise levels in 30-second epochs prior to the start of two or more consecutive runs with movement and prior to the start of two or more consecutive runs without movement.

## 5.8 RELATIONSHIP BETWEEN SYNCHRONOUS INDOOR NOISE EXPOSURE AND MOTILITY

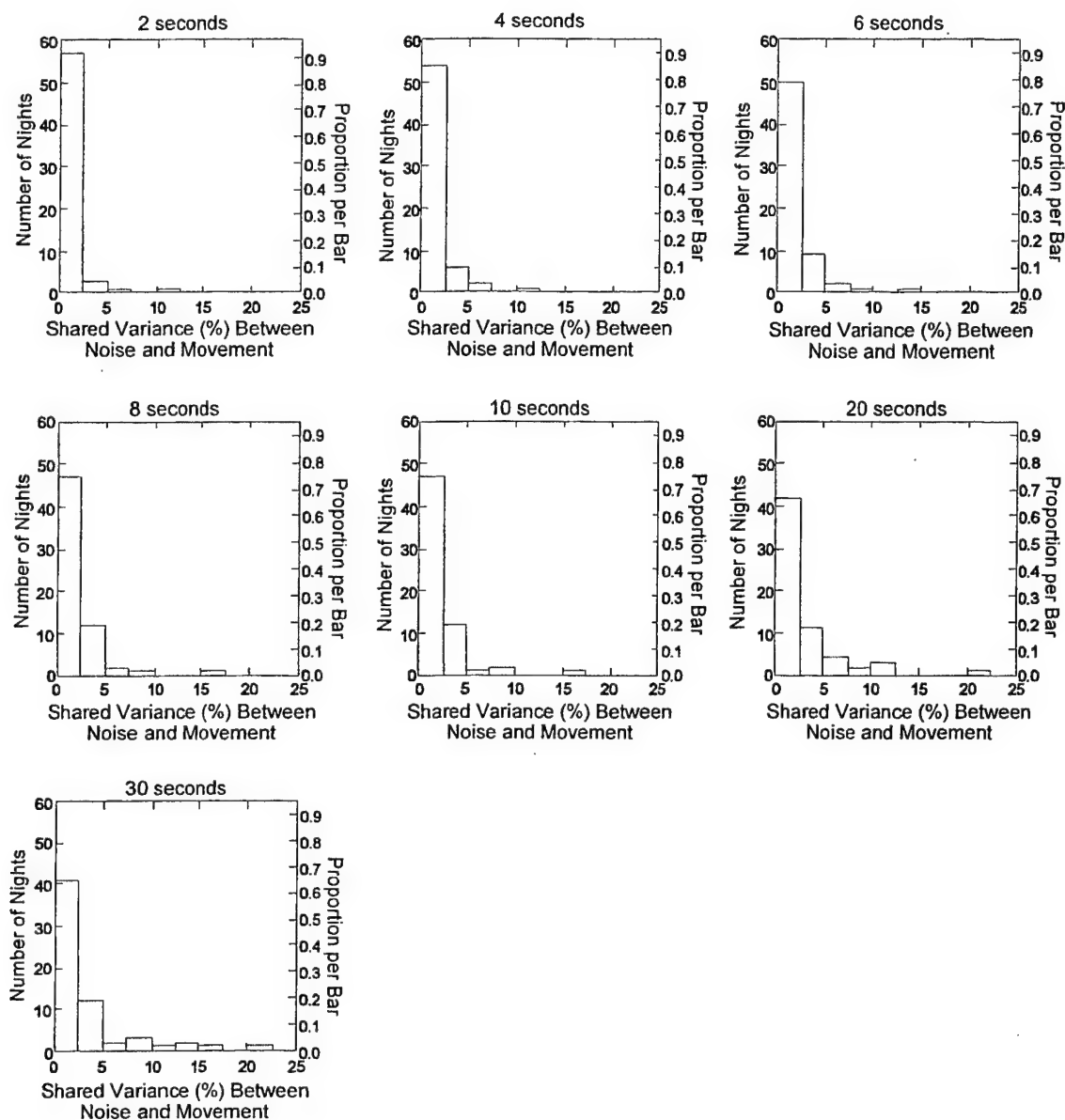
Pearson product-moment correlations of TAVA values of indoor noise with movement within epochs of varying duration were computed for each subject-night. Figure 21 shows histograms of percentages of shared variance between noise and motility for each subject-night in epochs of varying duration. A maximum correlation coefficient of  $r = .47$  was observed (on a single subject-night) in the 30- and 20-second epochs. In other words, no more than a quarter of the variance in zero crossings was ever associated with indoor noise levels in the entire data set. Correlation coefficients are smaller in shorter epoch durations because the ranges of zero crossings and TAVA of noise are truncated. This suggests that stronger association may be found among motility and indoor noise as measured in epoch durations even longer than 30 seconds.



**Figure 19** Representative time plots of 30-second TAVA values observed in various test participants' sleeping quarters.



**Figure 20** Distribution of indoor noise levels prior to start of runs of 2 or more consecutive epochs containing movement and runs lacking movement.



**Figure 21** Distribution of percent of shared variance between indoor noise level and movement for all subject-nights in epochs of varying duration.

## 6 DISCUSSION OF FINDINGS ABOUT DOSAGE-RESPONSE RELATIONSHIPS

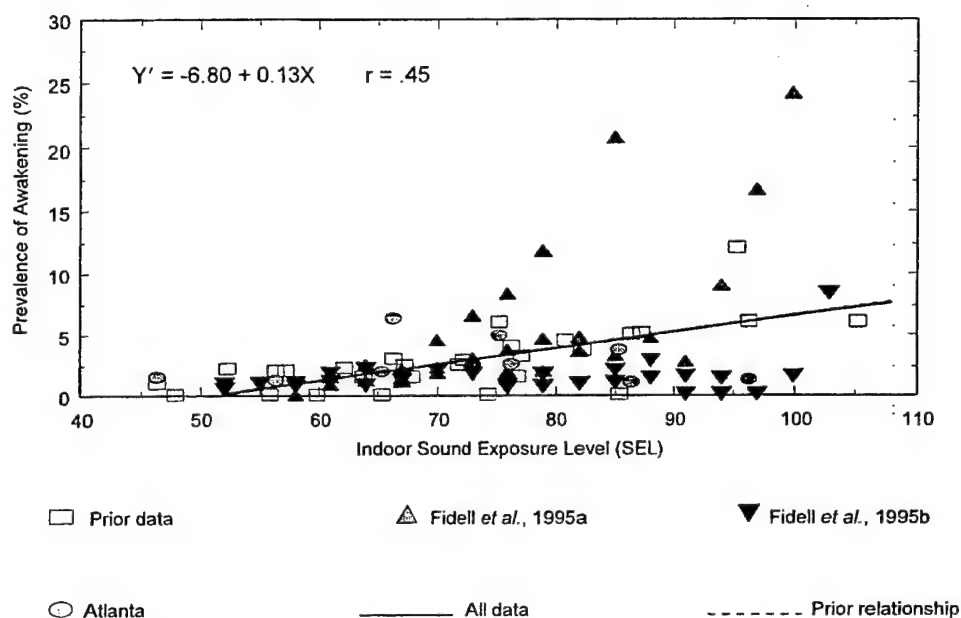
### 6.1 COMPARISON OF PRESENT WITH PRIOR FINDINGS

Table 13 compares the major characteristics of several recent field studies of the influence of aircraft noise on sleep disturbance.

**Table 13** Comparison of design features of the current study with Ollerhead *et al.* (1992) and Fidell *et al.* (1995a and 1995b).

| DESIGN FEATURE                 | OLLERHEAD <i>et al.</i> , 1992   | FIDELL <i>et al.</i> , 1995a  | FIDELL <i>et al.</i> , 1995b  | CURRENT STUDY   |
|--------------------------------|--|---|---|---|
| Venue                          | Eight neighborhoods near four British Airports   | Neighborhoods and individual sites near Castle AFB, LAX, and control areas  | Neighborhoods near two large civil airports near Denver, CO   | Neighborhood near DeKalb-Peachtree airport  |
| Independent variables          | Outdoor sound exposure levels produced by confirmed aircraft overflights   | Indoor and outdoor noise event levels   | Indoor and outdoor noise event levels; confirmed aircraft sound exposure levels   | Indoor and outdoor noise event levels   |
| Dependent variables            | Motility within 30 sec of a confirmed aircraft noise event, as measured by actimetric time-above-threshold criterion; some EEG                   | Behaviorally-confirmed awakening within varying time periods after occurrence of noise event  | Motility as measured by actimetric time-above-threshold and number of zero crossings within analysis epoch; behaviorally-confirmed awakenings within five minutes of noise event  | Motility as measured by number of zero crossings within analysis epoch; behaviorally-confirmed awakenings within five minutes of noise event  |
| Principal inferential analysis | Multiple logistic regression with <i>post hoc</i> definition of sleep disturbance sensitivity categories   | Multiple logistic regression  | Multiple logistic regression  | Multiple logistic regression  |
| Predictor variables considered | Outdoor aircraft noise event levels; age, gender, duration of residence, time of night, individual sensitivity, miscellaneous additional factors | Indoor and outdoor noise event levels, "whole-night" ambient levels; age, gender, duration of residence, time since retiring, time of night, duration of participation in study; self-rated tiredness; miscellaneous additional factors | Indoor and outdoor noise event levels, aircraft noise, "whole-night" ambient levels; age, gender, duration of residence, time since retiring, time of night, duration of participation in study; self-rated tiredness, miscellaneous additional factors | Indoor and outdoor noise event levels, "whole-night" ambient levels; age, gender, duration of residence, time since retiring, time of night, duration of participation in study; self-rated tiredness, miscellaneous additional factors |
| Subject-nights of observations | 5,742  | 1,857   | 2,717   | 686   |

Figure 22 plots the data from the current dosage-response relationship between SEL and behavioral awakenings along with data from the six field studies reviewed by Pearsons *et al.* (1995), the data from Ollerhead *et al.* (1992) adjusted by 15 dB to correspond with indoor sound levels, and the data from Fidell *et al.* (1995a and 1995b). The studies by Pearsons *et al.* 1995 and Ollerhead *et al.* 1992 are labeled "Prior data." Sources and numbers of noise events for each data point are tabulated in Appendix F.



**Figure 22** Composite of data from current study and findings of prior sleep disturbance field studies. (Prior relationship excludes Atlanta data.)

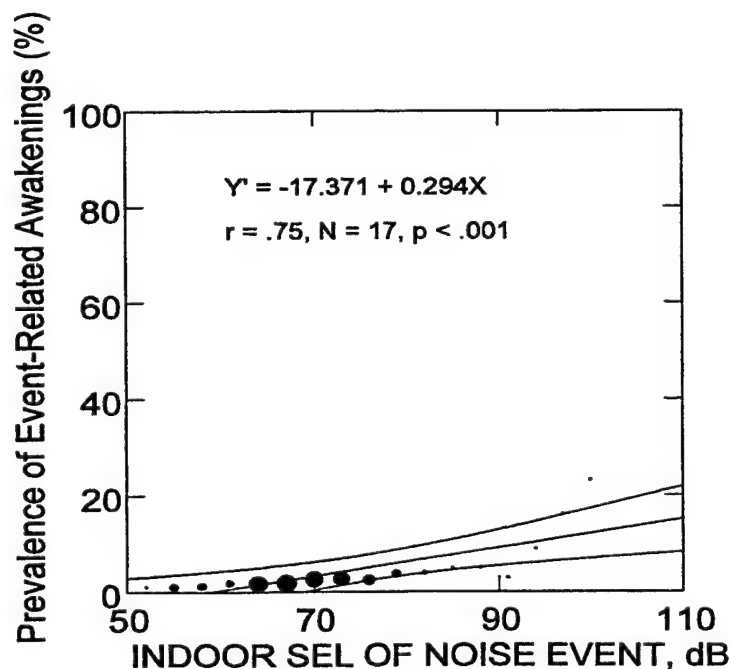
A probable explanation for the failure to observe a reliable dosage-response relationship in the current data between awakening and indoor SEL levels is the presence of masking by noise from mid-summer use of ventilating and air conditioning systems in Atlanta.<sup>11</sup> The pattern of present findings is nonetheless sufficiently similar to prior findings that a dosage-response relationship developed from the combination of prior and current data does not differ appreciably from the dosage-response relationship for prior data alone. The relationship is quite stable, but accounts for only about 20% of the variance in the data set. Each 10 dB increase in SEL increases the prevalence of awakening by only about 1.3%.

<sup>11</sup> Alternatively, the meaning of noise intrusions, rather than their audibility, may have a strong influence on arousal or awakening.

The dosage-response relationship shows much greater variability at higher than lower noise levels. For example, the range of prevalence of awakening at 60 dB is from 0 to about 2%. The range at 100 dB is from 0 to over 20%. Even long duration and/or high level noise events sometimes fail to awaken test participants.

The current data may be viewed in the context of the studies by Fidell *et al.* (1995a and 1995b), in which similar definitions of noise events and of awakening were applied. Figure 23 shows the dosage-response relationship with data combined over the three studies (Fidell *et al.* 1995a and 1995b and the current study). Note that the absence of a reliable relationship in the current data does not negate the reliability of findings of previous Fidell studies.

The aggregate of the earlier Fidell *et al.* (1995a and b) data (Figure 23) reveals a stronger relationship than that seen in Figure 22, in which several additional studies were analyzed. The aggregated Fidell data show an increase in awakening of almost 3% with each 10 dB increase in SEL, and a correlation of 0.75 — more than 50% of variance shared — between SEL and behavioral awakening. The Fidell data also show the presence of quadratic and cubic relationships, suggesting that the effect of indoor SEL on awakening becomes stronger at higher levels. The difference between the combined Fidell data and the relationship shown in Figure 22, which aggregates many diverse studies, may be attributed to the varying definitions of both awakening and noise events in



**Figure 23** Prevalence of behavioral awakening responses from two prior (Fidell *et al.* 1995a and 1995) and current studies aggregated by test participants in 3-dB intervals of indoor noise measurements. Curved lines bound the 95% confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events for the current and two prior studies.

the data plotted in Figure 22. Appendix G describes additional analyses of the combined Fidell data.

## **6.2 SEL AS A PREDICTOR OF SLEEP DISTURBANCE**

Current findings differ from some prior studies in definition of noise events, whether recorded inside participants' sleeping quarters or outside their residences. In past studies (*e.g.*, Fidell *et al.* 1995a and 1995b), minimum event durations were 2 seconds. Minimum event durations were set at 10 seconds in the current study, to better represent the noise of aircraft operations. Since events with durations of less than 10 seconds were excluded, fewer total events were collected. Consequently, relationships between sleep disturbance and SEL values in the current findings are not entirely comparable to those of previous studies. (Note that Figure 23 is based on a redefinition of events in Fidell *et al.* 1995a and 1995b to correspond to the current definition.)

Outdoor noise event levels, defined by a level threshold, were reliably related to participants' behaviorally-confirmed awakening as recorded by button pushes in the current data, but not to motility rates as measured actimetrically, or actimetrically-defined arousal. This is only partially consistent with Ollerhead's (1992) finding of a dosage-response relationship between outdoor noise levels and motility. However, both the actimeters used to measure motility in the current study and the noise measures employed were different from those used by Ollerhead.

A reliable dosage-response relationship was found between indoor SEL of noise events and arousal as determined by Cole *et al.*'s (1992) algorithm applied to the actimeter data, but not between indoor SEL and behavioral awakening as recorded by button pushes or motility as measured actimetrically. This is not entirely consistent with prior findings of small but highly reliable relationships between SEL measured indoors and several indicators of sleep disturbance, including awakening and motility as well as arousal.

## **6.3 ROLE OF OTHER PREDICTORS OF SLEEP DISTURBANCE**

Multiple logistic regression analysis revealed a few predictors of sleep disturbance (as measured by behavioral awakening responses and arousals as defined actimetrically) independent of SEL measured outdoors for behavioral awakening responses and indoors for arousal responses. However, in neither analysis was SEL a reliable predictor of sleep disturbance. That is, the dosage-response relationships failed to be replicated with the methodology employed in these analyses, which were based on individual events rather than events averaged over all participants and nights within 3-dB intervals.

Spontaneous awakening was positively associated with behavioral awakening and negatively associated with arousals. That is, participants with high rates of awakening in the absence of noise events are more likely to awaken in the presence of noise events, but less susceptible to arousal responses in the presence of noise events.

Probability of awakening decreased by about 1% with each subsequent night in the study, but the probability of an arousal response increased by about 2% with each subsequent night in the study.

Probability of arousal also increased by about 50% with each 1-unit increase in self-reported tiredness the prior evening. About 4-5% of the variance in sleep was accounted for by the full set of predictors in these logistic regression analyses.

## **6.4 EFFECTS OF CHANGES IN FLIGHT OPERATIONS**

Neither the increase in flight operations prior to the Olympic Games nor the decrease in operations following their end reliably affected the number of behavioral awakenings, recalled time to fall asleep, recalled time spent awake during the night, or motility. A general decrease in behavioral awakening responses over the data collection period was not shared by all participants. This apparent habituation to data collection procedures was also observed in some data collection rounds by Fidell *et al.* (1995b).

Change in indoor TAVA with the changes in number of operations was not statistically significant. Outdoor noise levels increased by about 3 dB over the course of data collection. The minor effects of flight operations on outdoor noise level apparently were insufficient to disturb sleep.

Failure to find reliable changes in indoor noise levels may be related to season of the year and associated temperature control; *e.g.*, air conditioners or fans may be turned on.

## **6.5 RELATIONSHIPS AMONG INDICATORS OF SLEEP DISTURBANCE**

Weak but reliable relationships were observed between awakening as recorded by button pushes and motility as measured actimetrically (about 1% of variance shared), and between awakening and arousals, as defined actimetrically by Cole *et al.*'s (1992) criterion (about 3% of variance shared). A stronger relationship (about 27% of shared variance) was found between awakening as recorded by button pushes and recalled time spent awake.

## **6.6 COMPARISON OF CURRENT DOSAGE-RESPONSE RELATIONSHIP AND LOGISTIC ANALYSES WITH THOSE OF FIDELL *et al.* (1995a and 1995b)**

The dosage-response relationship between indoor SEL and behavioral awakening found by Fidell *et al.* (1995a and 1995b) was not confirmed by current data. However, the dosage-response relationship found in the current study between *outdoor* SEL and behavioral awakening is consistent with prior findings that the probability of awakening increases by about 1.5 to 2.5% with each 10 dB increase in SEL. The current study found an increase in arousal rate of about 5% with each 10 dB increase in indoor SEL as compared with about 2.5% found by Fidell *et al.* (1995b).

Dosage-response analyses in which the current data are combined with recent Fidell studies show that indoor SEL reliably predicts sleep disturbance by all three criteria: behavioral awakening, actimetric motility, and arousal as determined by Cole *et al.*'s (1992) algorithm (Appendix G). Also, as seen in Appendix G, SEL recorded outside participants' residences reliably predicts only behavioral awakening responses, not arousal nor motility response, when the current data are

combined with recent Fidell studies.

The average number of spontaneous behaviorally-confirmed awakenings per night was about the same as that found by Fidell *et al.* (1995b): about 1.5 per night. This was somewhat lower than that found by Fidell *et al.* (1995a). The average number of awakenings per night associated with noise events, however, was greater than that found in the prior studies: 0.42 per night in the current study as compared with about 0.22 for the prior studies.

Table 14 summarizes a comparison of the multiple logistic analyses of the current study and those of Fidell *et al.* (1995a and 1995b). The findings of the five analyses were not consistent with respect to noise level of events. The current study showed no reliable increase in awakening or arousal with increase in noise level whether measured indoors or outdoors, while Fidell *et al.* (1995a) reported a 6% increase in awakening and Fidell *et al.* (1995b) showed a 3% increase in awakening with increase in indoor noise level. Consistent with current findings, Fidell *et al.* (1995b) also found no reliable increase in arousal level with increase in indoor SEL.

Findings with respect to age were inconsistent. Current data indicated no effect of age; Fidell *et al.* (1995b) showed an increase in responsiveness with age (with younger and older participants more likely to be aroused than those in the 35-49 age group), and Fidell *et al.* (1995a) reported a decrease in responsiveness with age. Effect of spontaneous awakening rate was also inconsistent. The current study showed a greater probability of noise-induced awakenings, whereas Fidell *et al.* (1995a) found a lower probability of noise-induced awakenings on those nights with higher spontaneous rates of awakening. However, both the current study and Fidell *et al.* (1995b) found a reduced arousal rate associated with a greater spontaneous awakening rate. Fidell *et al.* (1995b) found no relationship between spontaneous and noise-induced rates of awakening.

The current study was the only one in which an effect of self-rating of tiredness was a reliable predictor of sleep disturbance: each 1-unit increase in the rating of tiredness was associated with a 50% increase in arousal rate. Only Fidell *et al.* (1995b) found an effect of gender: men showed a higher arousal rate.

The effect of ambient level found in prior studies was not evident in the current study whether considering indoor or outdoor SEL. The current study confirmed the effect of habituation over the data collection period found by Fidell *et al.* (1995b) in some data collection rounds.

Appendix G describes multiple logistic regression analyses in which the data from the current study are combined with those of Fidell *et al.* (1995a and 1995b). Table 23 in Appendix G summarizes the results of the four analyses: all three sleep disturbance measures as predicted by indoor SEL and other variables, and behavioral awakening as predicted by outdoor SEL and other variables. (Analyses were based on reliable dosage-response relationships for the combined data.) SEL, whether measured indoors or outdoors, was a reliable predictor by itself only of behavioral awakening and motility in these logistic regression analyses. These logistic regression analyses are less powerful than the dosage-response analyses in which sleep disturbance responses are aggregated over nights and participants. That is, arousal was not reliably predicted by indoor SEL alone,

Table 14

Comparison of current behavioral awakening and arousal logistic regression analysis results, using noise event data, with behavioral awakening and arousal findings reported by Fidell *et al.* (1995a and 1995b).

| PREDICTOR   | FINDINGS OF CURRENT ANALYSIS              |  | FINDINGS OF FIDELL <i>et al.</i> (1995b)     |   | FINDINGS OF FIDELL <i>et al.</i> (1995a)     | COMMENTS   |
|---|---|--|--|---|--|--|
|   | Behavior awakenings                       | Arousals                                 | Behavioral awakenings                        | Arousals  | Behavioral Awakenings                        |  |
| Noise level   | No reliable effect of outdoor noise level | No reliable effect of indoor noise level | Positive linear effect of indoor noise level | No reliable effect of indoor noise level                          | Positive linear effect of indoor noise level |  |
| Indoor ambient level  | No effect                                 | No effect                                | Negative linear effect                       | Negative linear effect  | Negative linear effect                       |  |
| Time of night   | No linear effect                          | No linear effect                         | No linear effect                             | No linear effect  | Positive linear effect                       | Defined as time since retiring                               |
| Nights in study   | Negative linear effect                    | Positive linear effect                   | Negative linear effect                       | Positive linear effect  | No linear effect                             |  |
| Spontaneous awakening rate  | Positive linear effect                    | Negative linear effect                   | No linear effect                             | Negative linear effect  | Negative linear effect                       |  |
| Age   | No linear effect, no quadratic effect     | No linear effect, no quadratic effect    | Positive linear effect, no quadratic effect  | Positive linear effect, younger and older more likely than middle | Negative linear effect                       | Quadratic effect not tested by Fidell <i>et al.</i> (1995a). |
| Gender  | No effect                                 | No effect                                | No effect                                    | Men more likely   | No effect                                    |  |
| Duration of residence   | No linear effect                          | No linear effect                         | No linear effect                             | No linear effect  | Positive linear effect                       |  |
| Tiredness   | No linear effect                          | Positive linear effect                   | No linear effect                             | Negative linear effect  | Positive linear effect                       |  |
| Performance of logistic model as predictor of awakening to noise events | $d' = 0.63$                               | $d' = 0.64$                              | $d' = 0.71$                                  | $d' = 0.63$   | $d' = 0.79$                                  |  |

although it was predictable from combinations of other variables.

SEL measured inside participants' sleeping quarters predicted about 4% of the variance in behavioral awakening responses. Addition of the set of additional predictors raised the predictable variance to 9%. SEL measured outside participants' homes predicted only 1% of the variance in behavioral awakening responses. Addition of the set of other variables raised predictable variance to 4%.

Thus, the strongest predictors of sleep disturbance were the set of variables that include SEL measured inside participants' sleeping quarters, and the sleep disturbance indicator best predicted was behavioral awakening as indicated by button pushes.

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## **7 DISCUSSION OF FINDINGS ABOUT MOTILITY IN EPOCHS OF VARYING DURATION**

The present findings provide little reason to believe that characterization of sleep motility in epochs of short duration offers practical benefits for measurement of noise-induced sleep disturbance. Autocorrelation analyses demonstrated that episodes of sleep motility persist for periods of minutes, rather than seconds; lengths of runs of consecutive epochs with and without movement all exhibit similar exponential decay, regardless of epoch duration; and the pattern of correlations between numbers of zero crossings and short-term equivalent noise levels reveal stronger associations between motility and noise levels as measured in longer, rather than shorter, epochs.

Rather than facilitating analyses of noise-induced sleep disturbance, characterization of sleep motility in epochs of short duration increases the costs of data collection, reduction and processing; can obscure individual differences among test participants; limits the range of appropriate inferential statistics; and complicates the interpretation of findings.

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## 8 CONCLUSIONS

Because no effort was made to rigorously define the complete population exposed to nighttime noise exposure, nor to obtain a representative sample of any wider population, conclusions drawn from the present study apply strictly only to test participants.

The following are among the major findings of the dosage-response study:

- The current findings generally resemble those of prior field studies of noise-induced sleep disturbance, except that outdoor, rather than indoor, noise levels reliably predicted behaviorally-confirmed awakenings.
- Outdoor TAVA increased about 3 dB during the conduct of the Olympic games.
- Indoor nighttime TAVA varied little during the conduct of the Olympic games from the periods before and after their conduct.
- The average number of behavioral awakenings was about 1.5 per night. The average number of spontaneous behavioral awakening responses (unassociated with noise events) was about 1 per night.
- A statistically reliable relationship was found between sound exposure levels of individual noise intrusions as measured outside the residence and test participants exhibiting a behavioral awakening response within five minutes of the occurrence of the intrusion. The linear relationship was

$$\% \text{ noise-coincident awakening} = -7.93 + 0.312 (\text{SEL})$$

However, this relationship was not evident in a logistic regression analysis in which noise events were evaluated individually.

- A statistically reliable relationship was found between sound exposure levels of individual noise intrusions as measured inside participants' sleeping quarters and an actimetrically-defined arousal response. The linear relationship was

$$\% \text{ noise-coincident arousal} = -24.13 + 0.53 (\text{SEL})$$

However, this relationship was not evident in a logistic regression analysis in which noise events were evaluated individually.

- Relationships among measures of sleep disturbance were reliable but weak.
- About 3% of variance was shared between behaviorally-confirmed

awakenings and actimetrically-defined arousals.

- The grand average from previous studies was

$$\% \text{ noise-coincident awakening} = -6.8 + .13 (\text{SEL})$$

- About 1% of variance was shared between behaviorally-confirmed awakenings and actimetrically-measured motility.
- About 27% of variance was shared between behaviorally-confirmed awakenings and self-reports of time spent awake.

The following is the major finding of the motility study:

- Epochs of 30 seconds provide more stable, analyzable, and interpretable motility data than are provided by epochs of shorter duration.

## 9 GLOSSARY

*Terms in this Glossary are defined in the sense in which they are used in the body of this report, not necessarily in their broadest sense.*

**$\alpha$ :** The probability of making a Type I error (*q.v.*).

**$AL_{\max}$ :** Symbol for maximum A-level (*q.v.*).

**Annoyance:** A general adverse attitude toward noise exposure.

**Analysis of variance:** Analysis of the relationship between one or more discrete independent variables and a single continuous dependent variable.

**ANOVA:** Abbreviation for analysis of variance (*q.v.*).

**A-weighted sound level:** A single number index of a broadband sound that has been subjected to the A-weighting network (*q.v.*)

**A-weighting network:** A frequency-equalizing function intended to approximate the sensitivity of the human hearing to sounds of moderate sound pressure level.

**$\beta$ :** The symbol for a standardized regression coefficient, indicating the change in standardized units in a criterion variable with a standard deviation change in a predictor variable. In multiple regression (*q.v.*), change is evaluated with all other predictor variables held constant.

**B:** The symbol for an unstandardized regression coefficient, indicating the change in a criterion variable predicted from a one-unit change in a predictor variable. In multiple regression (*q.v.*), change is evaluated with all other predictor variables held constant.

**Between-subjects analysis:** ANOVA in which each case provides data for only one level of a discrete independent variable, such as gender.

**Bivariate regression:** Statistical technique for assessing the prediction of a continuous dependent variable from a single continuous independent variable, and the linear correlation between the variables.

**BMDPLR:** Commercial statistical software for logistic regression analysis.

**Confidence interval:** The range of population values of a statistic (*e.g.*, a mean or regression line) that is reasonable within some probability level.

**Confounding:** A potential cause (the confound or confounder) of a response has not been controlled

and, therefore, cannot be isolated from the presumed causal agent (noise exposure).

**Covariate:** Variable for which statistical adjustment or control has been made.

**C-weighting network:** A frequency-equalizing function intended to approximate the sensitivity of the human hearing to sounds of high sound pressure level. Essentially limits the bandwidth to include only unweighted one-third octave band levels from 31.5 to 8000 Hz.

**$d'$ :** Abbreviation and symbol for the scalar index of signal detectability

**Day Average Sound Level:** Time-average sound level between 0700 and 2200 hours. Unit, decibel (dB); abbreviation, DL; symbol,  $L_d$ .

NOTE:

Day average sound level in decibels is related to the corresponding day sound exposure level,  $L_{Ed}$ , according to:

$$L_d = L_{Ed} - 10 \log(54000/1)$$

where 54,000 is the number of seconds in a 15-hour day.

**Day-Night Average Sound Level:** Twenty-four hour average sound level for a given day, after addition of 10 decibels to levels from 0000 to 0700 hours and from 2200 (10 p.m.) to 2400 hours. Unit, decibel (dB); abbreviation, DNL; symbol,  $L_{dn}$ .

NOTES:

1. Day-night average sound level in decibels is related to the corresponding day-night sound exposure level,  $L_{Edn}$ , according to:

$$L_{dn} = L_{Edn} - 10 \log(86400/1)$$

where 86,400 is the number of seconds in a 24-hour day.

2. A-frequency weighting is understood, unless another frequency weighting is specified explicitly.

**dB:** Abbreviation for decibel (*q.v.*).

**decibel:** Unit measure of sound pressure level and other kinds of levels. It is expressed mathematically as the product of 10 times the logarithm to the base 10 of the ratio of a quantity of interest to a reference quantity.

**Dependent variable:** The response variable (effect) in a statistical analysis.

**Direct logistic regression:** Logistic regression in which a set of variables are evaluated simultaneously for their influence in the assessment of the probability of an outcome.

**DNL:** Abbreviation for Day-Night Average Sound Level (*q.v.*).

**Dosage-response relationship:** A plot (and analysis) showing a response (*e.g.*, prevalence of disease or awakening) to a dose of noise exposure; also known as dosage-effect relationship.

**$\eta^2$ :** In analysis of variance (*q.v.*), the proportion of variance in the dependent variable associated with the independent variable.

**Effective Perceived Noise Level:** The perceived noise level of a single event that has been modified for the additional annoyance caused by duration and tones.

**EPNL:** Abbreviation for Effective Perceived Noise Level (*q.v.*).

**Equivalent Noise Level (or time-averaged sound level):** The sound level typical of the sound levels at a certain place during a stated time period. The time-averaged sound level in decibels is the level of the mean-square A-weighted sound pressure during the stated time period, with reference to the standard sound pressure of 20 micropascals.

**Hosmer-Lemeshow  $\chi^2$ :** An inferential goodness-of-fit test to assess how far a logistic regression model (*q.v.*) departs from observed data.

**Independent variable:** A presumed causal (or predictor) variable in a statistical analysis.

**$L_{10}$ :** Symbol for the level of noise that is exceeded 10% of the time.

**$L_{50}$ :** Symbol for the level of noise that is exceeded 50% of the time.

**$L_{eq}$ :** Symbol for equivalent noise level (*q.v.*), written as TAVA within text.

**Logistic regression:** A statistical technique for assessing the probability of an outcome from a set of other variables, also known as multiple logistic regression.

**Maximum A-level:** The maximum A-weighted sound level in a given time period.

**Maximum Sound Level; Maximum Frequency-weighted Sound Pressure Level:** Greatest fast (125-ms) A-weighted sound level within a stated time interval. Alternatively, slow (1000 ms) time-weighting and C-frequency-weighting may be specified. Unit, decibel (dB); abbreviation, MXFA; symbol,  $L_{AFmx}$  (or C and S).

**McFadden's  $\rho^2$ :** In logistic regression, the proportion of variance in the outcome predictable from

one or more predictor variables.

**Multicollinearity:** Extremely high relationships among variables, preventing stable statistical analysis.

**Multivariate ANOVA:** Analysis of the relationship between one or more discrete independent variable and multiple continuous dependent variables.

**Multiway frequency analysis:** Analysis of relationships among discrete independent variables.

**MXFA:** Abbreviation for maximum fast A-weighted sound level; symbol,  $L_{\max}$ .

**Night Average Sound Level:** Time-average sound level between 0000 and 0700 hours and 2200 and 2400 hours. Unit, decibel (dB); abbreviation, NL; symbol,  $L_n$ .

NOTE:

Night average sound level in decibels is related to the corresponding night sound exposure level,  $L_{En}$ , according to:

$$L_n = L_{En} - 10 \log (32400/1)$$

where 32,400 is the number of seconds in a 9-hour night.

**Odds ratio:** In logistic regression, the change in odds of an outcome with a one-unit increase in a predictor variable.

**One-sided test:** Inferential test in which differences only in one direction between two populations are evaluated or relationships between variables in only direction (positive or negative) are evaluated..

$\phi^2$ : The size of the relationship between discrete variables on a scale of 0 (no relationship) to 1.00 (perfect relationship).

**PNL:** Abbreviation for perceived noise level (*q.v.*)

**Perceived Noise Level:** A single number index obtained by a computational procedure that combines the 24 one-third octave frequency band sound pressure levels in bands centered from 50 to 10,000 Hz to obtain a single level. The number computed by this calculation procedure gives an approximation to the perceived noise level as judged by subjective experiment on a fundamental psychoacoustic basis. Perceived noise level is numerically equal to the sound pressure level of a reference sound that is judged by listeners to have the same perceived nosiness as the given sound. Perceived noise level is generally computed for each 0.5-second time interval during an aircraft flyover.

**Polynomial regression:** Bivariate regression (*q.v.*) in which relationships more complex than linear are evaluated.

**Power:** Sensitivity of a statistical analysis to finding a true difference among populations or relationship among variables, defined as  $1 - \beta$ .

**Planned contrast:** A pre-planned analysis in which component comparisons within a complex ANOVA are analyzed; for example, the difference between two levels (*e.g.*, time periods) of an independent variables, ignoring all other levels.

**Profile analysis of repeated measures:** A form of multivariate ANOVA (*q.v.*) in which cases provide data for all levels of a discrete independent variable, such as time period.

***r*:** Index of bivariate linear correlation, the relationship between two continuous variables.

**$R^2$ :** Symbol for squared multiple correlation, the variance in the criterion variable that is predictable from the set of predictor variables in multiple regression (*q.v.*).

**Random effects model:** An ANOVA model in which levels of the discrete independent variable (such as participants) are selected randomly.

**Receiver operating characteristic (ROC) curve:** A plot of the sensitivity of a receiver showing the proportion of hits (decision that an event has occurred when it has in fact occurred) as a function of false alarms (decision that an event has occurred when it has not in fact occurred). The area between the ROC curve and the major diagonal is a measure of  $d'$  (*q.v.*).

**SD:** Abbreviation for standard deviation.

**SEL:** Abbreviation for Sound Exposure Level (*q.v.*).

**Sound Exposure Level:** Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second; symbol,  $E$ .

NOTES:

1. If frequency weighting is not specified, A-frequency weighting is understood. If other than A-frequency weighting is used, such as C-frequency weighting, an appropriate subscript should be added to the symbol; *e.g.*,  $E_C$ .
2. Duration of integration is implicitly included in the time integral and need not be reported explicitly. For the sound exposure measured over a specified time interval such as one hour, a 15-hour day, or a 9-hour night, the duration should be indicated by the abbreviation or letter symbol, for example one-hour sound exposure (1HSE or  $E_{1h}$ ) for a particular hour; day sound exposure (DSE or  $E_d$ ) from 0700 to 2200 hours; and night sound exposure (NSE or  $E_n$ ) from 0000 to 0700 hours plus from 2200 to 2400 hours.
3. Day-night sound exposure (DNSE or  $E_{dn}$ ) for a 24-hour day is the sum of the day sound exposure and ten

times the night sound exposure.

4. Unless otherwise stated, the normal unit for sound exposure is the pascal-squared second.

**Sound Level; Weighted Sound Pressure Level:** Ten times the logarithm to the base ten of the ratio of A-weighted squared sound pressure to the squared reference sound pressure of  $20 \mu\text{Pa}$ , the squared sound pressure being obtained with fast (F) (125-ms) exponentially weighted time-averaging. Alternatively, slow (S) (1000-ms) exponentially weighted time-averaging may be specified; also C-frequency weighting. Unit, decibel (dB); symbol  $L_A$ ,  $L_C$ .

NOTES:

1. In symbols, A-weighted sound level  $L_{A\tau}(t)$  at running time  $t$  is:

$$L_{A\tau}(t) = 10 \log \left\{ \left[ (1/\tau) \int_{-\infty}^t p_A^2(\xi) e^{-(t-\xi)/\tau} d\xi \right] / p_0^2 \right\}$$

where  $\tau$  is the exponential time constant in seconds,  $\xi$  is a dummy variable of integration,  $p_A^2(\xi)$  is the squared, instantaneous, time-varying, A-weighted sound pressure in pascals, and  $p_0$  is the reference sound pressure of  $20 \mu\text{Pa}$ . Division by time constant  $\tau$  yields the running time average of the exponential-time-weighted, squared sound-pressure signal. Initiation of the running time average from some time in the past is indicated by  $-\infty$  for the beginning of the integral.

2. ANSI S1.4-1983, *American National Standard Specification for Sound Level Meters*, gives standard frequency weightings A and C and standard exponential time weightings fast (F) and slow (S).

**Sound Pressure; Effective Sound Pressure:** Root-mean-square instantaneous sound pressure at a point, during a given time interval. Unit, pascal (Pa).

NOTE:

In the case of periodic sound pressures, the interval is an integral number of periods or an interval that is long compared to a period. In the case of non-periodic sound pressures, the interval should be long enough to make the measured sound pressure essentially independent of small changes in the duration of the interval.

**Sound pressure level:** A measure of sound taken as ten times the common logarithm of the square of the ratio of sound pressure to the reference sound pressure of 20 micropascals. The frequency bandwidth must be identified.

**Statistical adjustment:** Holding adjusted variables constant in order to reveal the unique effect of other variables. See covariate.

**Stepdown analysis:** Supplemental analysis to multivariate ANOVA in which multiple dependent variables are evaluated in a pre-set priority order; each dependent variable, in turn, is evaluated after statistical adjustment for higher priority dependent variables.

**Subject-night:** The amount of data collected from one subject for one night.

**TAVA:** Abbreviation for time-averaged sound level (*q.v.*); symbol,  $L_{eq}$ .

**Time-averaged sound level:** The time-averaged sound level in decibels is the level of the mean-square A-weighted sound pressure during the stated time period, with reference to the standard sound pressure of 20 micropascals.

**Two-sided test:** Inferential test in which differences in either direction between two populations are evaluated or relationships between variables in only direction (positive or negative) are evaluated.

**Type I error:** Declaring populations different when in fact they are not different, or relationships among variables to exist when they do not.

**Type II error:** Failure to declare populations different when in fact they are different, or failing to find relationships among variables when in fact they exist.

**Within-subjects analysis:** ANOVA in which cases provide data for all levels of a discrete independent variable, such as time period, also known as repeated measures ANOVA.

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## 10 REFERENCES

- Cole, R., D. F. Kripke, W. Gruen, D. Mullaney, & J. C. Gillin (1992). "Automatic Sleep/Wake Identification From Wrist Activity," *Sleep*, 15(5), pp. 461-469.
- FICON (Federal Interagency Committee on Noise) (1992). Final Report, Airport Noise Assessment Methodologies and Metrics, Washington, D.C. See also FICON (Federal Interagency Committee on Noise) (1992). Federal Agency Review of Selected Airport Noise Analysis Issues, Committee Recommendations, Washington, D.C.
- Fidell, S., K. Pearsons, B. Tabachnick, R. Howe, L. Silvati, & D. Barber (1995a). "Field study of noise-induced sleep disturbance," *J. Acoust. Soc. Am.*, 98(2), pp. 1025-1033.
- Fidell, S., R. Howe, B. Tabachnick, K. Pearsons, & M. Sneddon (1995b). "Noise-Induced Sleep Disturbance in Residences Near Two Civil Airports," NASA Langley Research Center Contract No. NAS1-20101, NASA Contractor Report 198252, Hampton, VA.
- Health Council of the Netherlands: Committee on uniform environmental noise exposure metric, (1997). "Assessing noise exposure for public health purposes," Rijswijk: Health Council of the Netherlands, Publication No. 1997/23E.
- Öhrström, E. (1993). "Research on noise and sleep since 1998: Present state," in *Noise and Man '93: Noise as a Public Health Problem*, Actes INRETS No. 34, M. Valet, ed., Arcueil, France.
- Öhrström, E., & Griefahn, B. (1993), "Effects of Noise on Sleep," in *Noise and Man '93: Noise as a Public Health Problem*, Actes INRETS No. 34, M. Valet, ed., Arcueil, France.
- Ollerhead, J. B., C. J. Jones, R. E. Cadoux, A. Woodley, B. J. Atkinson, J. A. Horne, F. Pankhurst, L. Reyner, K. I. Hume, F. Van, A. Watson, I. D. Diamond, P. Egger, D. Holmes, & J. McKean (1992). *Report of a Field Study of Aircraft Noise and Sleep Disturbance* (London: Department of Safety, Environment and Engineering).
- Pearsons, K., D. Barber, B. Tabachnick, & S. Fidell (1995). "Analysis of the predictability of noise-induced sleep disturbance," *J. Acoust. Soc. Am.*, 97, pp. 331-338.
- Tabachnick, B. G., & L. S. Fidell (1996). *Using Multivariate Statistics*, Third Ed., Addison-Wesley-Longman (formerly HarperCollins Publishers Inc.): New York, NY.

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## **APPENDIX A      RECRUITING PROCEDURES AND INSTRUCTIONS TO TEST PARTICIPANTS**

### **A.1    LETTERS OF SOLICITATION TO TEST PARTICIPANTS (ROUND 1 ONLY)**

The initial mailing to prospective test participants under Round 1 of this study included a letter of explanation on Air Force letterhead, a letter on BBN letterhead, and a return form with a stamped, pre-addressed envelope. The wording of the Air Force letter was as follows:

"The U.S. Air Force has been conducting research on noise-induced sleep disturbance at a number of sites around the country as part of its federally-mandated effort to evaluate and establish environmental standards. DeKalb-Peachtree and Fulton County Airports are two sites that are being considered for study during July and August of this year. As described in the attached letter, BBN Corporation is acting as the Air Force's contractor for this research. BBN scientists are seeking interested parties in your neighborhood to participate in this study. Your participation would assist the Air Force in its on-going efforts to understand and predict the environmental impacts of aircraft noise on residents of airport neighborhoods.

I would like to thank you in advance for your cooperation in this important research endeavor. Please call me at Wright-Patterson Air Force Base, OH [phone number] if you should have any questions about participating in this study."

The wording of the BBN letter was as follows:

"Dear Sir or Madam:

BBN is planning a scientific study of nighttime sleep disturbance in your neighborhood during July and August 1996. People who take part in this study will be paid to push a button if they wake up at night, and will wear a wristwatch-like device that measures arm motion. We would like to tell you more about this study, and to find out if you or other adult members of your family might be interested in being paid to take part in it.

If you are interested in learning more about the study, please fill out and mail the attached form in the stamped return envelope. Returning the form does not obligate you to take part in the study, nor does it ensure that you are eligible to take part. BBN will, however, contact you to explain details of the study. You may also call BBN toll free [1-800-number] at your convenience for additional information."

Prospective test participants were asked to provide information on the returned form useful for contacting them and assessing their suitability for participation.

## **A.2 INSTRUCTIONS TO TEST PARTICIPANTS**

Test participants were given an instruction booklet following a telephone interview to determine their suitability for the experiment. Field technicians explained the questionnaire and use of the actigraphs and palmtop computers to test participants during an initial visit to install the instrumentation. The participants were provided with an 800 telephone number throughout the experiment to ask questions or report problems that arose. Weekly telephone calls were made to set up equipment maintenance appointments, at which time any additional questions were answered.

The instruction booklet is reproduced on the following pages.

# Sleep Study Instructions



If you have any questions, please call  
**1-800-XXX-XXXX**

---

## **YOUR JOB IN THE SLEEP STUDY**

This booklet explains what you are expected to do in the sleep study.

### **You have four things to do every day:**

- |    |  |
|----|--|
| 1. | Wear the wrist device.   |
| 2. | Answer the Nighttime Questionnaire on the small computer before you go to sleep for the night. |
| 3. | Push the red button if you wake up for any reason during the night.                            |
| 4. | Answer the Morning Questionnaire on the small computer when you get out of bed in the morning  |

### WHAT TO DO JUST BEFORE YOU GO TO BED AT NIGHT:

1. If you have not already done so, place the wrist device on your non-favored arm. If you are right-handed, put it on your left wrist and if you are left-handed, put it on your right wrist.
2. Make sure that the two black cables are firmly plugged into the small computer, and that the computer is plugged into a wall outlet.
3. Make sure that the red button you push when you wake up is within easy reach of your bed.
4. Open the hinged top of the small computer by lifting the lid from the front. If the screen is blank, press the "ON" button in the upper right-hand corner of the keyboard.
5. Press the "F10" key (toward the right of the top row of buttons) to start the nighttime questionnaire.
6. Answer the question by picking the number which best describes your answer, then press the "ENTER" key. Turn to page 72 for an explanation of the nighttime question.  
  
If you make a mistake in your answer, you can correct it by pressing the "ESC" key in the upper left corner of the keyboard and answering the question again.
7. After you have answered the question and *you are ready to go to sleep*, press "F10" again to set the computer for the night. You may leave the computer lid open or closed as you like. *Do not* turn the computer off.

**Note:** You should answer the question only once each night as you are about to go to bed, *not* each time you wake up during the night.

### NOTES ABOUT USING THE WRIST DEVICE:

You do not have to do anything with the wrist device other than wear it. At a minimum, you must wear the device from the time you go to bed at night until you get out of bed in the morning. If you like, you may wear it longer, even 24 hours a day.

Please remember that the wrist device is delicate and should be treated as you would an expensive wristwatch. Do not drop the device onto the floor or place it on any table or surface where it might be knocked off onto the floor.

The wrist device is not waterproof and should not be worn while you bathe.

### WHAT TO DO DURING THE NIGHT:

Press the red button once only, right away, *each time* you wake up for any reason at all during the night. If you stay awake for a while after pushing the button, **do not** press the button again.

If you forget to press the button when you wake up during the night, and you then stay awake for more than five minutes, **do not** press the button.

If you stay awake for a while after you wake up during the night and you can't remember (or are not sure) if you pushed the button when you first woke up, **do not** press the button again.

REMEMBER: Press the red button *ONCE*, as soon as you wake up, each time you wake up for any reason at all.

### WHAT TO DO WHEN YOU WAKE UP IN THE MORNING:

1. As soon as you wake up in the morning press the red button once.
2. If you closed the lid of the small computer the previous evening, open it by lifting the lid from the front.
3. Press the "F10" key. You will then be asked to estimate how many times you woke up during the night. Press the number on the keypad in the lower right corner of the keyboard and press "ENTER."
4. Answer each of the following questions by picking the number which best describes your answer, then pressing the "ENTER" key. Turn to page 72 for an explanation of each of the morning questions.

If you make a mistake in your answer, you can correct it by pressing the "ESC" key in the upper left corner of the keyboard and answering the question again.

If you forget to answer the morning questionnaire when you get up, then answer the questions as soon as you remember.

You should take off the wrist device and place it in the protective case when not in use.

### **WHAT TO DO IF YOU TAKE A NAP DURING THE DAY:**

You don't have to do anything with the equipment if you take a nap during the day. There is no need for any interview or to push the button before or after napping.

### **IF YOU HAVE OTHER QUESTIONS:**

If you have any questions about the study procedures or experience any difficulty in operating any of the equipment, please call

**1-800-XXX-XXXX**

### **HOW TO ANSWER THE NIGHTTIME QUESTION:**

There is only one question to answer before you go to bed at night:

#### **How tired did you feel today?**

Please pick the phrase that best describes how you felt throughout the entire day (not just at the time you are answering the question). Your choices are:

1. Not at all tired
2. Slightly tired
3. Moderately tired
4. Very tired
5. Extremely tired

Press the number on the keypad in the lower right-hand corner of the keyboard corresponding to your choice.

### **HOW TO ANSWER THE MORNING QUESTIONS:**

#### **How many times did you wake up last night?**

Please estimate the number of times you woke up last night. Type in the number and press "ENTER."

#### **How well did you sleep last night?**

Please tell us how well you slept last night. Your choices are:

1. Not at all well
2. Fairly well
3. Moderately well
4. Very well
5. Extremely well

**How long did it take you to fall asleep?**

Please estimate how long it took you to fall asleep when you first went to bed last night. Your choices are:

1. Less than 10 minutes
2. 10 - 20 minutes
3. 20 - 30 minutes
4. 30 - 60 minutes
5. more than an hour

**How much were you awake last night?**

Please estimate the total amount of time you were awake during the night after you first went to sleep. For example, if you woke up twice during the night and were awake for approximately five minutes each time, then you were awake for a total of about 10 minutes. In this case, you should answer "10-20 minutes." If you did not wake up at all during the night, or if you fell back to sleep quickly after awakening, answer "Less than 10 minutes." Your choices are:

1. Less than 10 minutes
2. 10 - 20 minutes
3. 20 - 30 minutes
4. 30 - 60 minutes
5. more than an hour

**How annoyed were you by noise last night?**

If you heard any noise during the night (whether you were awakened by it or you were already awake), how annoyed were you by the noise? Your choices are:

1. Did not hear any noise last night
2. Not at all annoyed by noise last night
3. Slightly annoyed by noise last night
4. Moderately annoyed by noise last night
5. Very annoyed by noise last night

6. Extremely annoyed by noise last night

## APPENDIX B      SUMMARY OF NIGHTTIME NOISE ENVIRONMENTS

Tables 15 through 17 summarize the noise event data at PDK that are analyzed in Section 4. Outdoor noise levels are estimated from the closer of two outdoor measurement locations.

**Table 15**      Summary of noise measurements at test participants' homes before Olympic Games.

| SITE          | TOTAL NUMBER OF NOISE EVENTS |              | NUMBER OF NOISE EVENTS BETWEEN 2200 AND 0700 HOURS |              | AVERAGE EVENT A-WEIGHTED MXFA (dB) |         |
|---------------|------------------------------|--------------|--|--------------|------------------------------------|---------|
|               | Inside                       | Outside      | Inside   | Outside      | Inside                             | Outside |
| A             | 7                            | 97           | 6  | 71           | 58.6                               | 76.4    |
| B             | 27                           | 606          | 26   | 237          | 67.9                               | 75.7    |
| C             | 104                          | 69           | 96   | 66           | 66.4                               | 75.3    |
| D             | 93                           | 408          | 91   | 228          | 70.4                               | 75.9    |
| E             | 376                          | 348          | 228  | 54           | 66.7                               | 77.1    |
| F             | 90                           | 279          | 51   | 177          | 72.2                               | 75.5    |
| G             | 171                          | 392          | 98   | 144          | 68.8                               | 76.5    |
| H             | 25                           | 607          | 18   | 285          | 64.4                               | 76.4    |
| I             | 37                           | 564          | 9  | 84           | 62.0                               | 76.3    |
| J             | 20                           | 304          | 16   | 245          | 57.6                               | 75.8    |
| K             | 8                            | 220          | 2  | 58           | 66.7                               | 76.4    |
| L             | 19                           | 406          | 14   | 165          | 63.3                               | 75.5    |
| <b>TOTALS</b> | <b>977</b>                   | <b>4,300</b> | <b>655</b>   | <b>1,814</b> |                                    |         |

**Table 16** Summary of noise measurements at test participants' homes during Olympic Games.

| SITE          | TOTAL NUMBER OF NOISE EVENTS |              | NUMBER OF NOISE EVENTS BETWEEN 2200 AND 0700 HOURS |              | AVERAGE EVENT A-WEIGHTED MXFA (dB) |         |
|---------------|------------------------------|--------------|--|--------------|------------------------------------|---------|
|               | Inside                       | Outside      | Inside   | Outside      | Inside                             | Outside |
| A             | 38                           | 517          | 25   | 376          | 62.5                               | 75.2    |
| B             | 84                           | 728          | 67   | 308          | 57.1                               | 76.0    |
| C             | 61                           | 72           | 61   | 70           | 65.5                               | 75.5    |
| D             | 17                           | 526          | 16   | 343          | 69.5                               | 74.1    |
| E             | 241                          | 219          | 133  | 81           | 66.1                               | 76.6    |
| F             | 73                           | 304          | 46   | 217          | 74.2                               | 74.3    |
| G             | 107                          | 473          | 105  | 205          | 69.6                               | 75.4    |
| H             | 15                           | 920          | 9  | 438          | 64.0                               | 75.2    |
| I             | 40                           | 678          | 5  | 176          | 66.7                               | 76.6    |
| J             | 18                           | 529          | 16   | 419          | 57.6                               | 74.5    |
| K             | 38                           | 349          | 0  | 131          | 60.2                               | 76.3    |
| L             | 5                            | 246          | 3  | 131          | 59.1                               | 75.7    |
| <b>TOTALS</b> | <b>737</b>                   | <b>5,561</b> | <b>486</b>   | <b>2,895</b> |                                    |         |

**Table 17** Summary of noise measurements at test participants' homes after Olympic Games.

| SITE          | TOTAL NUMBER OF NOISE EVENTS |              | NUMBER OF NOISE EVENTS BETWEEN 2200 AND 0700 HOURS |            | AVERAGE EVENT A-WEIGHTED MXFA (dB) |         |
|---------------|------------------------------|--------------|--|------------|------------------------------------|---------|
|               | Inside                       | Outside      | Inside   | Outside    | Inside                             | Outside |
| A             | 49                           | 190          | 45   | 106        | 65.9                               | 77.1    |
| B             | 80                           | 154          | 79   | 47         | 66.0                               | 77.6    |
| C             | 10                           | 40           | 3  | 29         | 74.5                               | 72.4    |
| D             | 60                           | 136          | 20   | 62         | 67.7                               | 77.2    |
| E             | 250                          | 261          | 156  | 58         | 69.4                               | 77.1    |
| F             | 33                           | 94           | 23   | 75         | 71.5                               | 77.1    |
| G             | 2                            | 41           | 2  | 23         | 82.1                               | 77.4    |
| H             | 6                            | 156          | 6  | 80         | 63.1                               | 75.6    |
| I             | 12                           | 131          | 6  | 22         | 61.7                               | 77.7    |
| J             | 3                            | 83           | 3  | 51         | 61.7                               | 77.2    |
| K             | —                            | 117          | —  | 19         | —                                  | 76.9    |
| L             | 3                            | 29           | 3  | 12         | 57.5                               | 80.0    |
| <b>TOTALS</b> | <b>508</b>                   | <b>1,432</b> | <b>346</b>   | <b>584</b> |                                    |         |

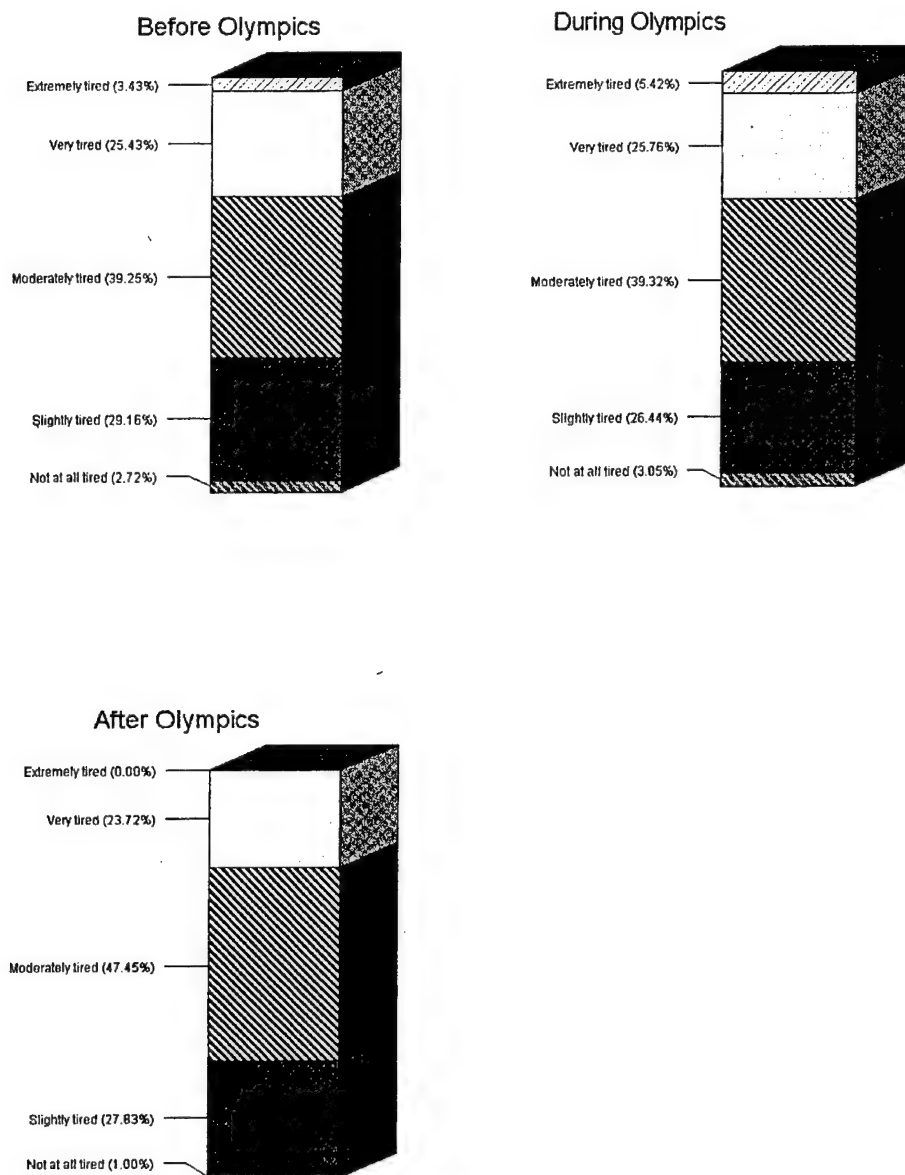
## **APPENDIX C      SUMMARY OF INTERVIEW DATA**

### **C.1    SUMMARY OF NIGHTTIME INTERVIEWS**

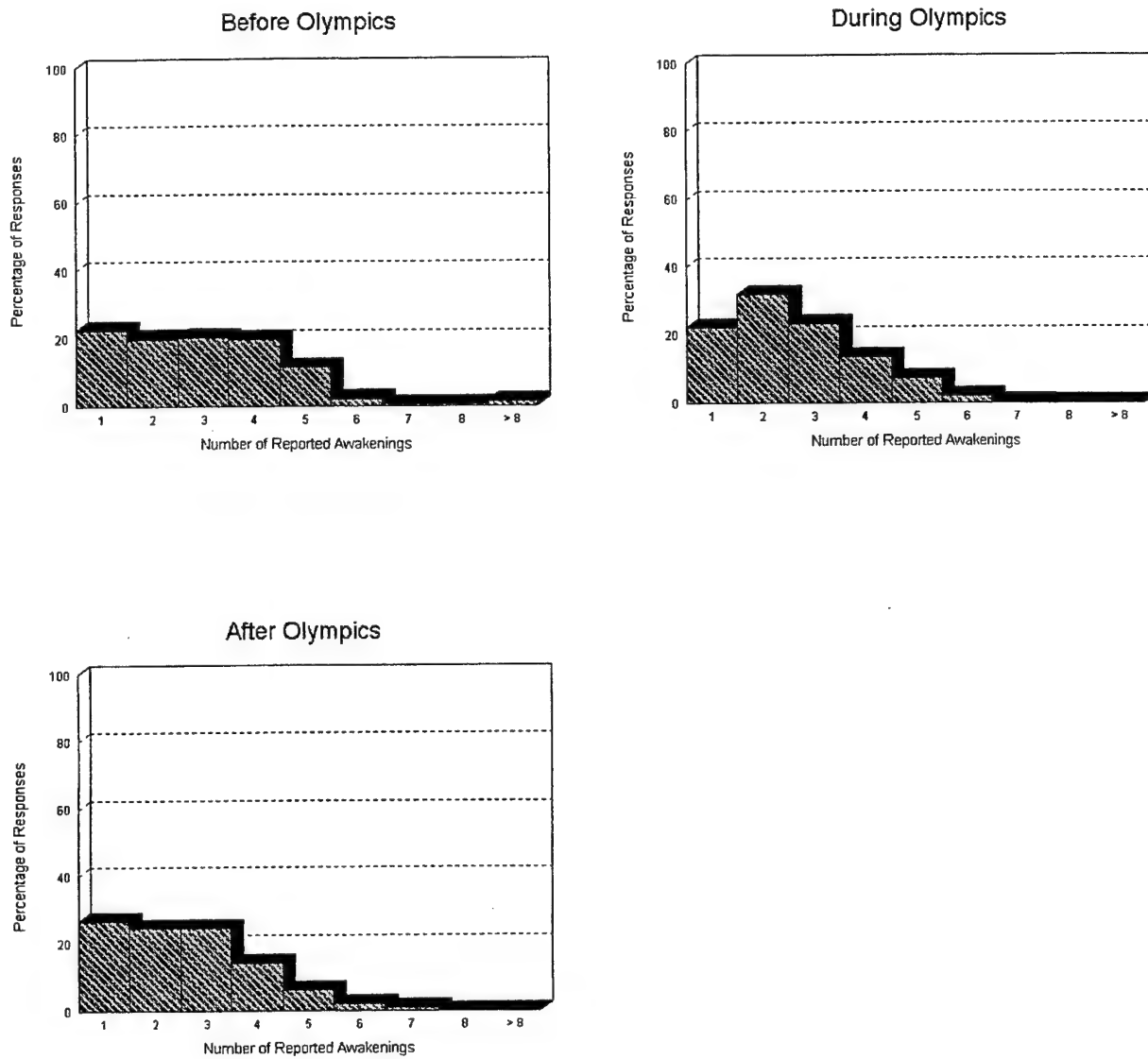
Figure 24 describes responses to the nighttime interview question based on data from 686 subject-nights. Responses are described separately for three phases of data collection at PDK.

### **C.2    SUMMARY OF MORNING INTERVIEWS**

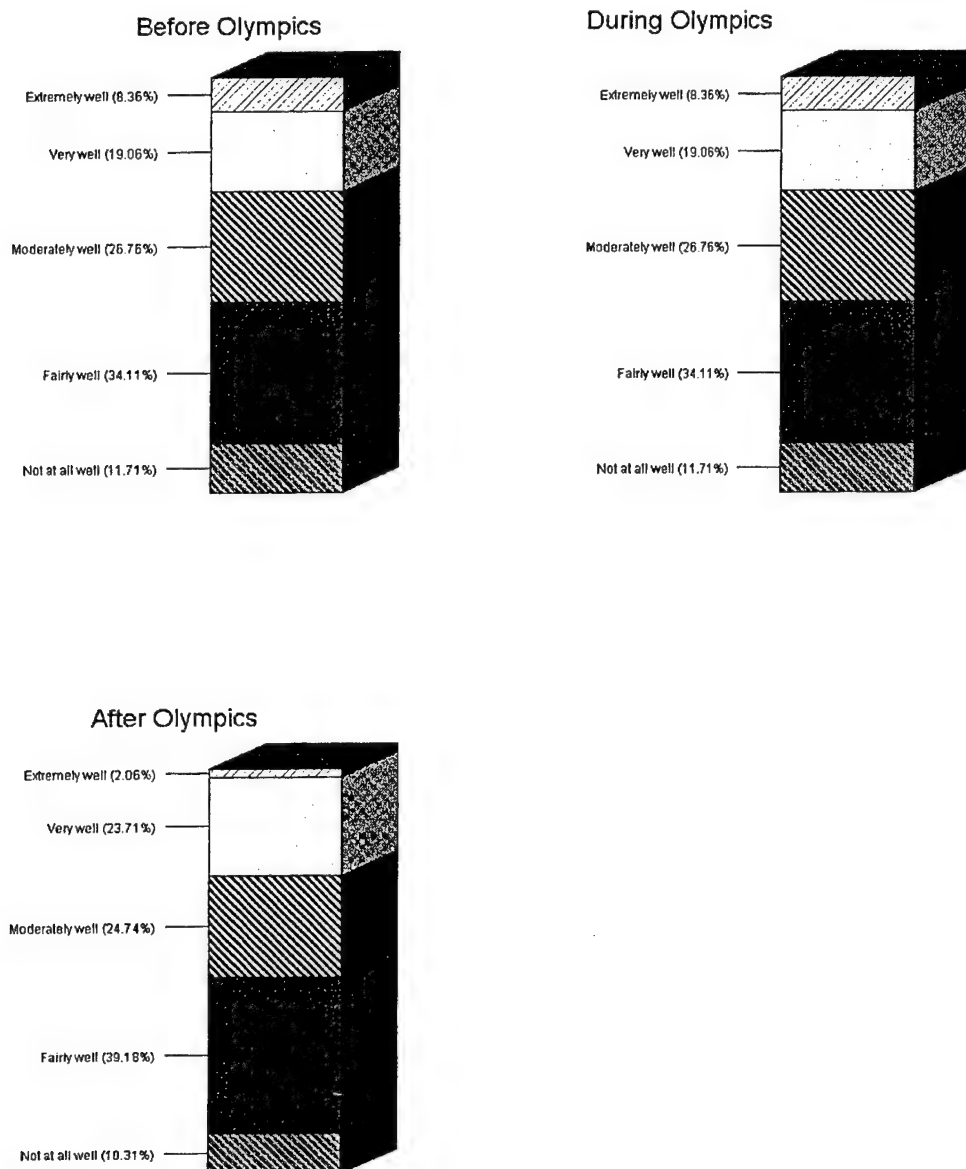
Figures 25 through 29 describe the results of the morning interview questionnaire based on data from 686 subject-nights. Each figure describes responses separately for three phases of data collection at PDK.



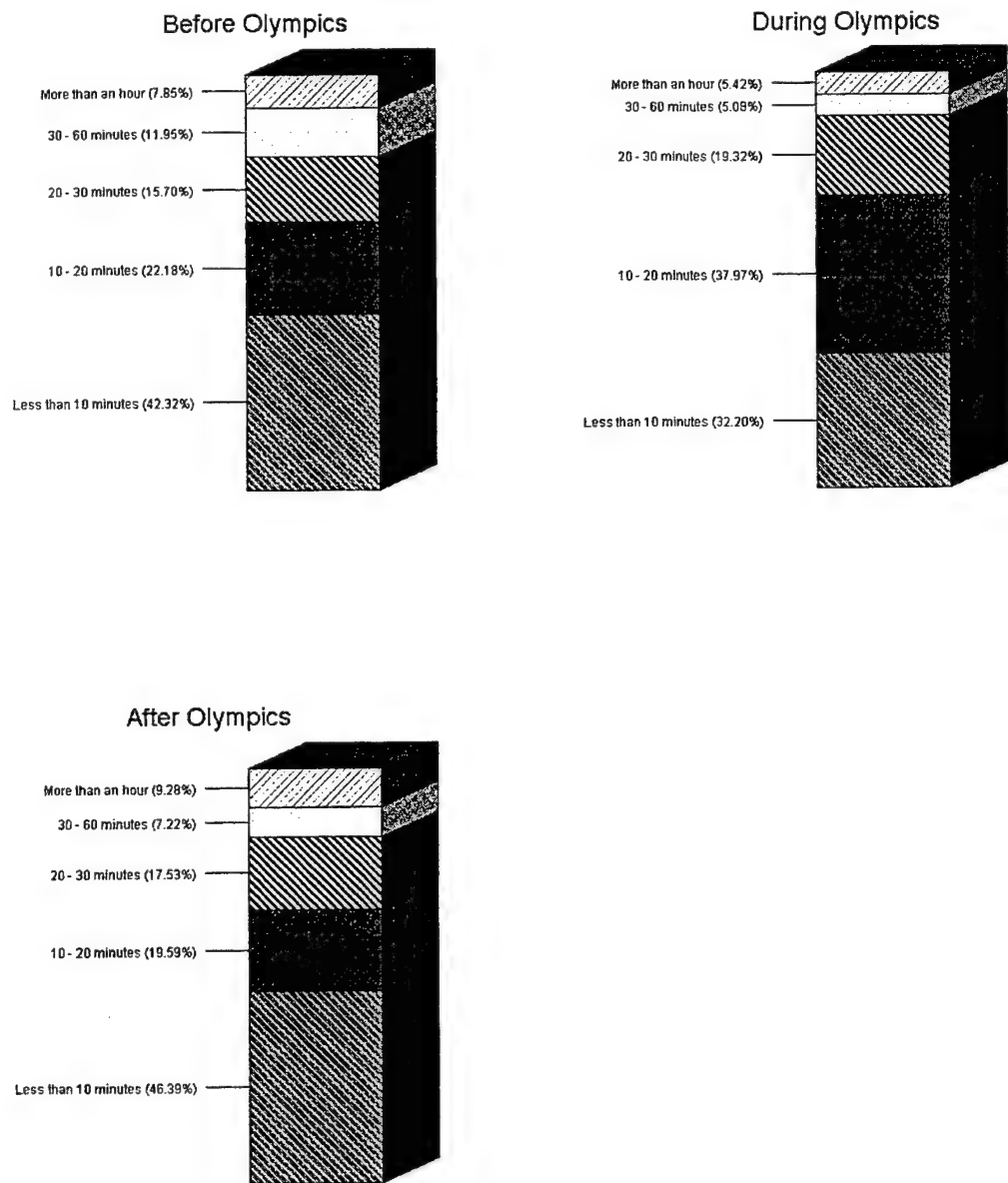
**Figure 24** Summary of responses to "How tired did you feel today?"



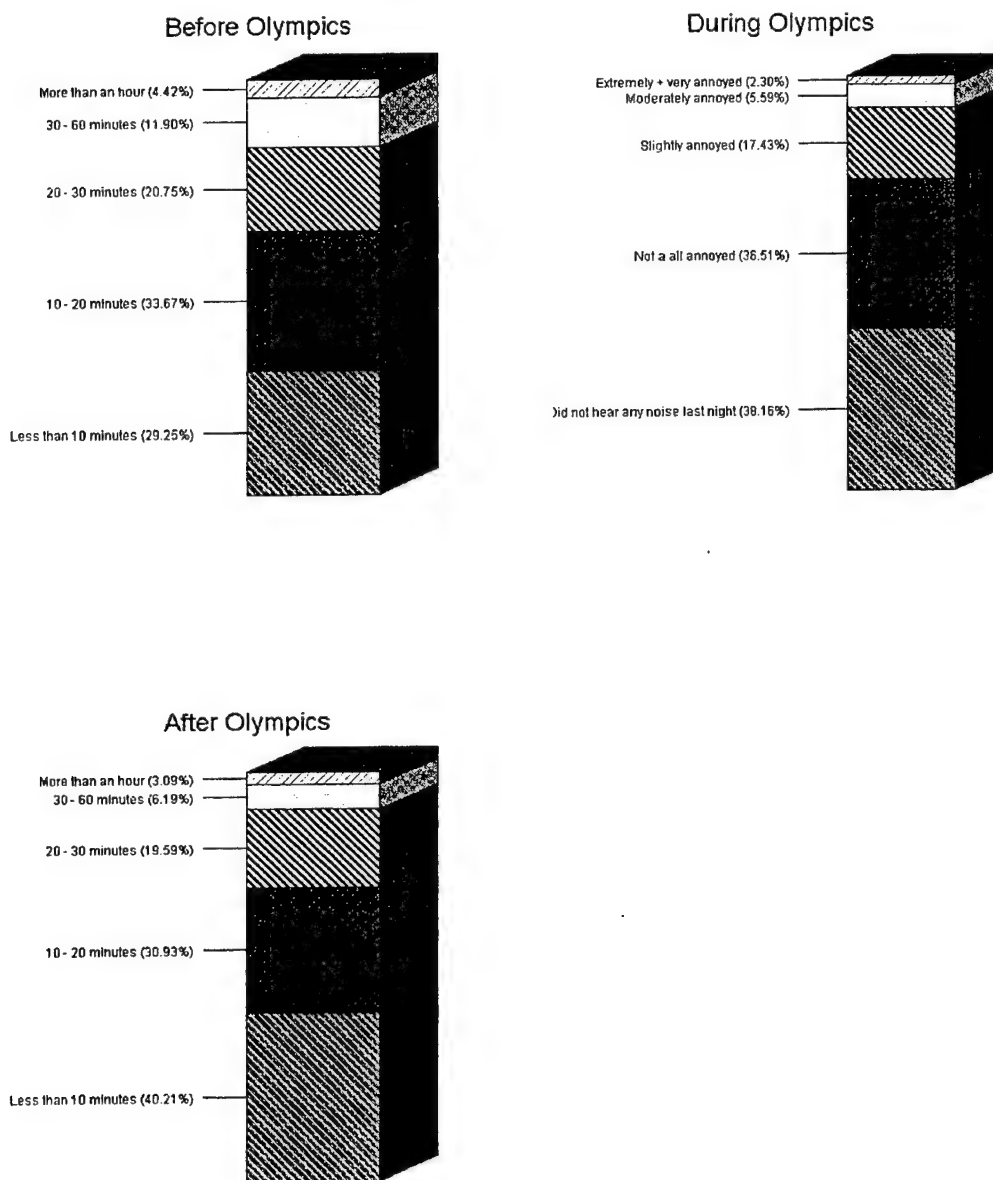
**Figure 25** Summary of responses to "How many times did you wake up last night?"



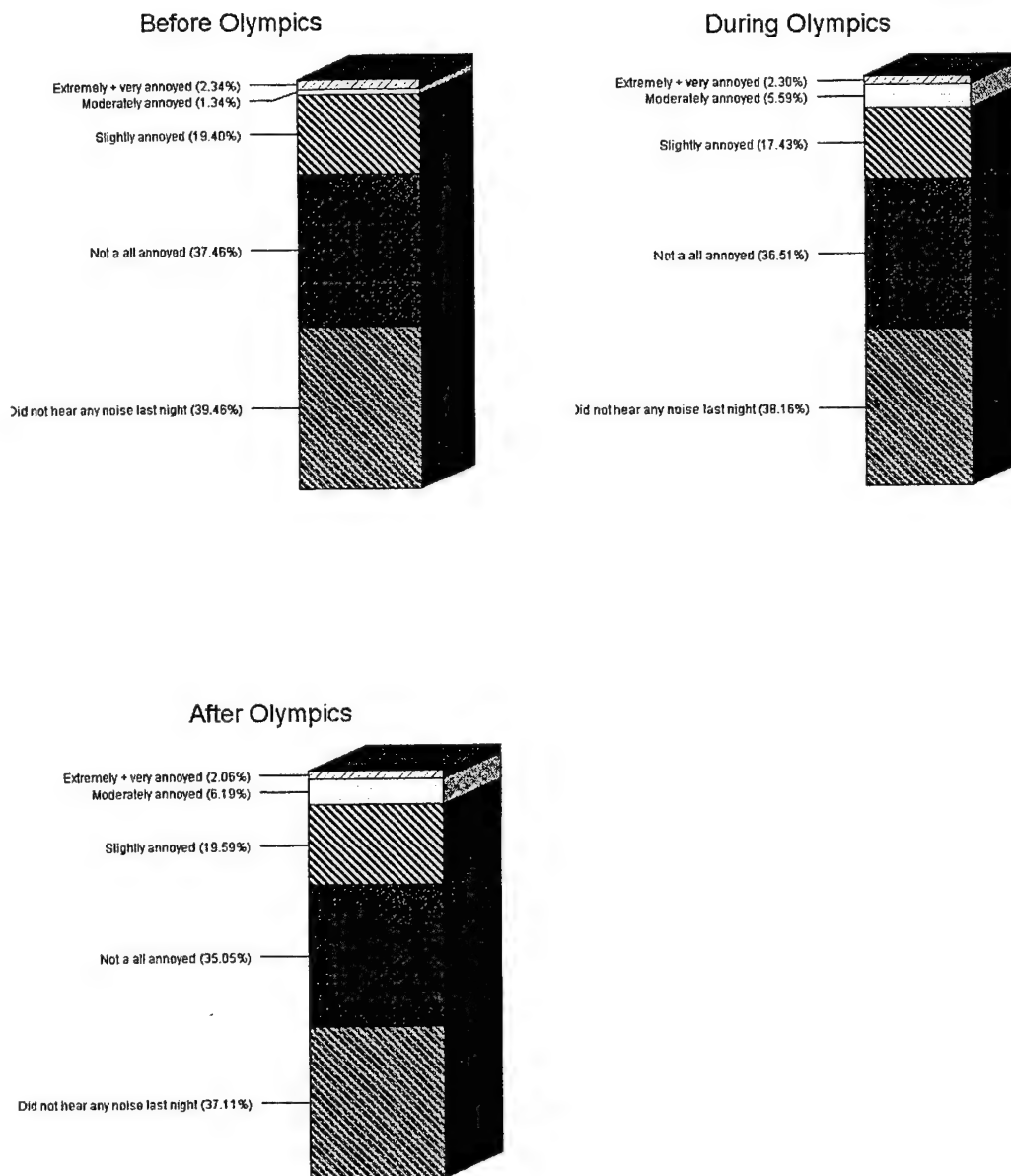
**Figure 26** Summary of responses to "How well did you sleep last night?"



**Figure 27** Summary of responses to "How long did it take you to fall asleep last night?"



**Figure 28** Summary of responses to "How much were you awake last night?"



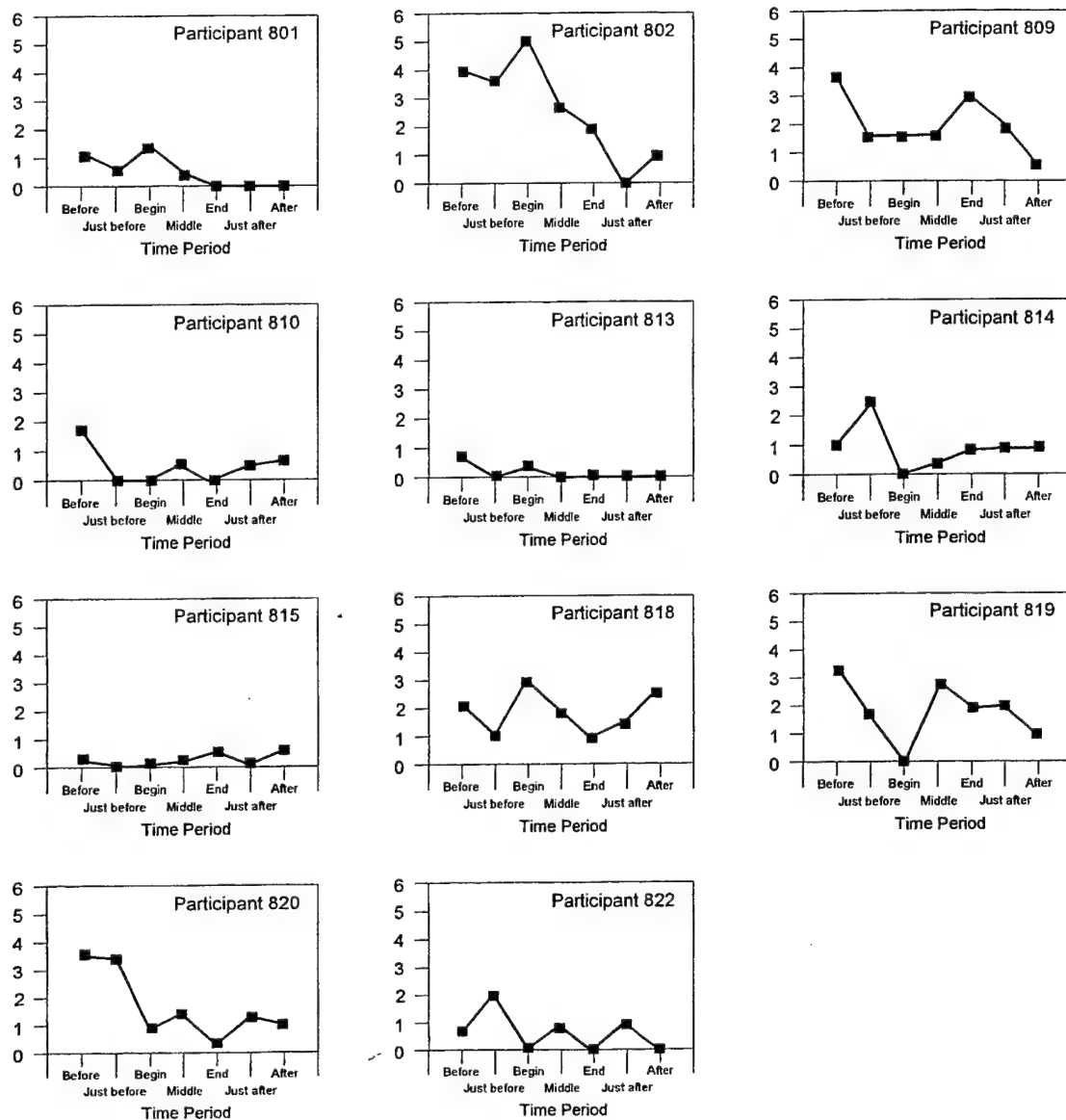
**Figure 29** Summary of responses to "How annoyed were you by noise last night?"

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## **APPENDIX D      BEHAVIORAL AWAKENING RESPONSES ON SUCCESSIVE NIGHTS AT PDK**

Figure 30 plots behavioral awakenings (button pushes) for the 11 residents who provided valid data over all time periods tracked. Nights are grouped into seven periods:

1. Several nights of data collection (following the first three nights for each participant) prior to two nights before the start of the Olympics (2-14 July);
2. The two nights before the start of the Olympics (15 and 16 July);
3. The first two nights after the start of the Olympics (17 and 18 July);
4. Mid-Olympic nights (19 July to 2 August);
5. The last two nights of the Olympics (3 and 4 August);
6. The first two nights after the end of the Olympics (5 and 6 August); and
7. The remaining nights of data collection (7-11 August).



**Figure 30** Behavioral awakenings (button pushes) for 11 test participants at PDK over all time periods.

## APPENDIX E      RESULTS OF LOGISTIC REGRESSION ANALYSIS

Tables 18 and 19 provide details of the behavioral logistic regression analysis by noise events, as discussed in Section 4. The tables show the regression coefficients for each of 10 predictors, the odds ratios, 95% confidence interval for the odds ratios, and the contribution of each predictor to the model.

Regression coefficients ( $B$ ) are useful as indications of the direction of the relationship to each predictor with the probability of sleep disturbance. Positive coefficients indicate that an increase in the value of the predictor results in an increase in the probability of awakening. The relative magnitudes of the coefficients do not indicate the relative strength of unique contribution to prediction of each variable, because variables are measured on different scales.

The odds ratio is a more easily interpreted transformation of the regression coefficient, defined as  $e^B$ . An odds ratio that is greater than one indicates (a) that the likelihood of sleep disturbance increases with increasing magnitude of the predictor, and (b) the extent of increase in likelihood. For example, an odds ratio of 2 indicates that as the predictor increases by one unit, the odds in favor of disturbance doubles. Regression coefficients and their associated odds ratios are estimated values, subject to sampling error. The 95% confidence limits bound the likely range of values (odds ratios) given the sample data. A variable significantly enhances prediction of awakening (at  $\alpha = .05$ ) if the confidence limits on its associated odds ratio do not include 1.0.

The last column in Table 18 presents the results of a series of analyses of each sleep disturbance measure in which models are formed with each predictor separately removed from the full model containing all predictors. The performance of the reduced model for each predictor is then compared with the full model. A statistically significant result indicates that the model without a given predictor does a significantly poorer job of predicting sleep disturbance than one that includes that predictor, and thus serves as a test of the significance of prediction for that variable. This latter test is preferable to tests of variables based on confidence limits for odds ratios.

**Table 18** Prediction of an awakening by button push following within five minutes of noise events recorded outdoors between 2200 and 0700 hours.

| VARIABLE (UNIT)   | B      | ODDS RATIO<br>PER UNIT | 95% CONFIDENCE INTERVAL<br>FOR ODDS RATIO |       | F TO REMOVE |
|---|--------|------------------------|---|-------|-------------|
|   |        |                        | Lower                                     | Upper | df=1, 5,766 |
| Personal Characteristics                                  |        |                        |   |       |             |
| Number of spontaneous awakenings (inverted and reflected) | 0.907  | 2.98                   | 1.37                                      | 4.50  | 9.09 *      |
| Gender  | -0.245 | 0.78                   | 0.55                                      | 1.12  | 1.86        |
| Age (linear, years)                                       | 0.006  | 1.01                   | 0.99                                      | 1.02  | 0.54        |
| Age (quadratic, 35-49 vs. others)                         | -0.141 | 0.87                   | 0.55                                      | 1.29  | 0.50        |
| Time-Related Characteristics                              |        |                        |   |       |             |
| Time since retiring (in 15 minute increments)             | 0.019  | 1.02                   | 1.01                                      | 1.04  | 4.66        |
| Duration of residence (months)                            | -0.001 | 1.00                   | 1.00                                      | 1.00  | 2.06        |
| Number of nights in study                                 | -0.031 | 0.97                   | 0.95                                      | 0.99  | 14.00 *     |
| Pre-Sleep Characteristics                                 |        |                        |   |       |             |
| Tiredness on retiring (scale of 1 to 5)                   | 0.224  | 1.25                   | 1.03                                      | 1.52  | 5.07        |
| Noise Characteristics                                     |        |                        |   |       |             |
| Ambient level (dB)  | -0.016 | 0.98                   | 0.95                                      | 1.02  | 0.82        |
| SEL (dB)  | 0.026  | 1.03                   | 1.00                                      | 1.05  | 4.24        |

\*  $p < .005$ .

Table 19

Prediction of an arousal as defined by Cole *et al.* (1992) following events recorded indoors between 2200 and 0700 hours.

| VARIABLE (UNIT)   | B      | ODDS RATIO<br>PER UNIT | 95% CONFIDENCE INTERVAL<br>FOR ODDS RATIO |       | F TO REMOVE<br>df=1, 5,766 |
|---|--------|------------------------|---|-------|----------------------------|
|   |        |                        | Lower                                     | Upper |                            |
| Personal Characteristics                                  |        |                        |   |       |                            |
| Number of spontaneous awakenings (inverted and reflected) | -1.081 | 0.34                   | 0.19                                      | 0.62  | 12.71 *                    |
| Gender  | 0.255  | 1.29                   | 0.89                                      | 1.88  | 1.70                       |
| Age (linear, years)                                       | 0.001  | 1.00                   | 0.98                                      | 1.02  | 0.01                       |
| Age (quadratic, 35-49 vs. others)                         | 0.333  | 1.39                   | 0.91                                      | 2.14  | 2.24                       |
| Time-Related Characteristics                              |        |                        |   |       |                            |
| Time since retiring (in 15 minute increments)             | 0.018  | 1.02                   | 1.00                                      | 1.04  | 2.98                       |
| Duration of residence (months)                            | -0.000 | 1.00                   | 1.00                                      | 1.00  | 0.00                       |
| Number of nights in study                                 | 0.018  | 1.02                   | 1.01                                      | 1.03  | 7.98 *                     |
| Pre-Sleep Characteristics                                 |        |                        |   |       |                            |
| Tiredness on retiring (scale of 1 to 5)                   | 0.403  | 1.50                   | 1.19                                      | 1.88  | 11.80 *                    |
| Noise Characteristics                                     |        |                        |   |       |                            |
| Ambient level (dB)  | -0.024 | 1.02                   | 1.00                                      | 1.05  | 5.44                       |
| SEL (dB)  | 0.027  | 1.03                   | 1.00                                      | 1.06  | 3.29                       |

\*  $p < .005$ .

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# APPENDIX F      TABULATIONS OF DATA FOR DOSAGE-RESPONSE RELATIONSHIP

Table 20 shows the sources of all data points found in Figure 22 of Section 6.

**Table 20**      Sources of all data points.

| STUDY                                  | NOISE SOURCE(S) | SEL   | PERCENT AWAKENED | NUMBER OF EVENTS   |
|--|-----------------|-------|------------------|--|
| Vallet, M. <i>et al.</i> (1980)        | Aircraft        | 46.3  | 1                | 5 to 35 stimuli per night, 10 male participants, 4 nights      |
|  |                 | 56.3  | 2                |  |
|  |                 | 66.3  | 3                |  |
|  |                 | 76.3  | 4                |  |
|  |                 | 86.3  | 5                |  |
|  |                 | 96.3  | 6                |  |
| Pearsons, K. <i>et al.</i> (1972)      | Aircraft        | 65.3  | 0                | 1.4 stimuli per night, 5 nights, 5 couples                     |
|  |                 | 75.3  | 6                |  |
|  |                 | 85.3  | 0                |  |
|  |                 | 95.3  | 12               |  |
|  |                 | 105.3 | 6                |  |
| Vernet, M. (1979)                      | Rail            | 47.8  | 0                | 1 night, 20 participants, number of stimuli not recorded       |
|  |                 | 55.8  | 0                |  |
|  |                 | 59.8  | 0                |  |
|  |                 | 63.8  | 1.5              |  |
|  |                 | 67.8  | 1.5              |  |
|  |                 | 71.8  | 2.5              |  |
|  |                 | 76.8  | 1.5              |  |
| Rylander, R., (1972)                   | Traffic         | 74.3  | 0                | 251 participants, 7 nights, number of stimuli not recorded     |
|  |                 |       |                  |  |
| Ollerhead, J. B., <i>et al.</i> (1992) | Aircraft        | 52.2  | 2.16             | A total of 4,823 aircraft events during 120 measurement nights |
|  |                 | 57.2  | 2                |  |
|  |                 | 62.2  | 2.24             |  |
|  |                 | 67.2  | 2.44             |  |
|  |                 | 72.2  | 2.88             |  |
|  |                 | 77.2  | 3.16             |  |
|  |                 | 82.2  | 3.68             |  |
|  |                 | 87.2  | 5.08             |  |

| STUDY                            | NOISE SOURCE(S)     | SEL | PERCENT AWAKENED | NUMBER OF EVENTS |
|----------------------------------|---------------------|-----|------------------|------------------|
| Fidell, S. <i>et al.</i> (1995a) | Ambient             | 58  | 0                | 33               |
|                                  |                     | 61  | 0.9              | 108              |
|                                  |                     | 64  | 2.4              | 210              |
|                                  |                     | 67  | 2.1              | 281              |
|                                  |                     | 70  | 4.5              | 178              |
|                                  |                     | 73  | 6.5              | 124              |
|                                  |                     | 76  | 8.3              | 60               |
|                                  |                     | 79  | 11.8             | 34               |
|                                  | Military aircraft   | 64  | 2.5              | 197              |
|                                  |                     | 67  | 1.1              | 184              |
|                                  |                     | 70  | 1.8              | 331              |
|                                  |                     | 73  | 3                | 332              |
|                                  |                     | 76  | 1.9              | 583              |
|                                  |                     | 79  | 4.6              | 610              |
|                                  |                     | 82  | 3.6              | 447              |
|                                  |                     | 85  | 3.2              | 317              |
|                                  |                     | 88  | 4.7              | 343              |
|                                  |                     | 91  | 2.7              | 291              |
|                                  |                     | 94  | 9                | 233              |
|                                  |                     | 97  | 16.6             | 157              |
|                                  |                     | 100 | 24.1             | 79               |
|                                  | Commercial aircraft | 61  | 1.5              | 67               |
|                                  |                     | 64  | 1.2              | 1150             |
|                                  |                     | 67  | 1.4              | 1507             |
|                                  |                     | 70  | 2.2              | 998              |
|                                  |                     | 73  | 2.8              | 616              |
|                                  |                     | 76  | 3.7              | 354              |
|                                  |                     | 79  | 1.9              | 212              |
|                                  |                     | 82  | 4.7              | 85               |
|                                  |                     | 85  | 20.7             | 29               |

| STUDY                            | NOISE SOURCE(S)     | SEL | PERCENT<br>AWAKENED | NUMBER OF EVENTS |
|----------------------------------|---------------------|-----|---------------------|------------------|
| Fidell, S. <i>et al.</i> (1995b) | Commercial aircraft | 52  | 0.5                 | 444              |
|                                  |                     | 55  | 0.9                 | 2137             |
|                                  |                     | 58  | 0.7                 | 1829             |
|                                  |                     | 61  | 1.1                 | 1124             |
|                                  |                     | 64  | 0.8                 | 1183             |
|                                  |                     | 67  | 1.2                 | 888              |
|                                  |                     | 70  | 1.9                 | 638              |
|                                  |                     | 73  | 1.8                 | 1047             |
|                                  |                     | 76  | 0.6                 | 1175             |
|                                  |                     | 79  | 1.7                 | 933              |
|                                  |                     | 82  | 0.9                 | 969              |
|                                  |                     | 85  | 2                   | 904              |
|                                  |                     | 88  | 1.3                 | 622              |
|                                  |                     | 91  | 1.5                 | 536              |
|                                  |                     | 94  | 1.3                 | 230              |
|                                  |                     | 97  | 0                   | 109              |
|                                  |                     | 100 | 1.5                 | 67               |
|                                  |                     | 103 | 8.3                 | 24               |
|                                  | Ambient             | 52  | 0.9                 | 540              |
|                                  |                     | 55  | 0.9                 | 2121             |
|                                  |                     | 58  | 1                   | 1904             |
|                                  |                     | 61  | 1.8                 | 1135             |
|                                  |                     | 64  | 2.1                 | 1262             |
|                                  |                     | 67  | 1.5                 | 1009             |
|                                  |                     | 70  | 1.9                 | 790              |
|                                  |                     | 73  | 1.7                 | 605              |
|                                  |                     | 76  | 0.8                 | 490              |
|                                  |                     | 79  | 0.7                 | 827              |
|                                  |                     | 82  | 0.9                 | 568              |
|                                  |                     | 85  | 1                   | 304              |
|                                  |                     | 88  | 2.8                 | 143              |
|                                  |                     | 91  | 0                   | 63               |
|                                  |                     | 94  | 0                   | 34               |

| STUDY         | NOISE SOURCE(S)     | SEL | PERCENT<br>AWAKENED | NUMBER OF EVENTS |
|---------------|---------------------|-----|---------------------|------------------|
| Current study | Commercial aircraft | 61  | 1.5                 | 67               |
|               |                     | 64  | 1.2                 | 82               |
|               |                     | 67  | 6.3                 | 63               |
|               |                     | 70  | 2.5                 | 276              |
|               |                     | 73  | 1                   | 484              |
|               |                     | 76  | 1.2                 | 258              |
|               |                     | 79  | 1.9                 | 106              |
|               |                     | 82  | 4.9                 | 82               |
|               |                     | 85  | 3.7                 | 54               |

## APPENDIX G      RESULTS OF EVENT-BASED COMBINED ANALYSES

Noise events observed by Fidell *et al.* (1995a and 1995b) were redefined in accordance with current criteria<sup>12</sup> and combined with the current data. Dosage-response and logistic regression analyses then were performed on the combined data set, which included a total of 19,158 events recorded inside residents' sleeping quarters and 24,543 events recorded outside their residences. (Note that data from Fidell *et al.* (1995a) included only events recorded indoors.)

Thus the combined data set included data from three sites in California (LAX, Castle AFB, and areas in the vicinity of Los Angeles not exposed to aircraft overflight noise), two sites in Denver, Colorado (DEN and DIA, recorded before and after transfer of operations from DEN to DIA), and one site in Atlanta, Georgia (in the vicinity of DeKalb-Peachtree Airport, recorded before, during, and after the 1996 Olympic Games).

### G.1    DOSAGE-RESPONSE ANALYSES

#### G.1.1   Dosage-Response Relationships

All dosage-response relationships were restricted to noise event data collected between 2200 and 0700 hours, since earlier time periods in the evening and later time periods in the morning contained too high a density of noise events for reliable association with individual responses. Dosage-response relationships were constructed for three indicators of sleep disturbance:

1.    behavioral awakening responses (button pushes),
2.    arousals as defined by Cole *et al.* (1992) criterion for the actimetric data, and
3.    motility as recorded actimetrically.

The independent (predictor) variable for all dosage-response relationships was either indoor or outdoor SEL, quantized in 3-dB intervals. Data points reflect the proportion of noise events in each noise level interval that produced a response. Data were combined for all test participants and all data collection sessions for behavioral awakening and actimeter responses. Table 21 shows the definitions of awakening, arousal, and motility adopted for the two data collection devices.

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<sup>12</sup> In the Fidell *et al.* 1995a and 1995b studies, minimum event durations were 2 seconds. Noise events in the current study were defined as a time series of noise levels that began when a pre-set threshold was exceeded for at least 10 seconds, and that continued until the level remained more than 2 dB below the pre-set threshold.

**Table 21** Definitions of awakening and motility adopted for various data collection devices.

| INDICATION OF SLEEP DISTURBANCE | RECORDING DEVICE | CRITERION OF EFFECT  |
|---------------------------------|------------------|--|
| Awakening                       | Push button      | Occurrence of response within five minutes of start of noise event                         |
| Arousal                         | Actimeter        | As defined by Cole <i>et al.</i> (1992), using base algorithm without iteration            |
| Motility                        | Actimeter        | Any activity occurring in any of the ten 30-second epochs after the start of a noise event |

One-sided analyses of significance of associations of sleep disturbance and noise events were tested at  $\alpha = .005$ . Any 3-dB interval containing fewer than 25 noise events was excluded from analysis.

Correlations for the various dosage-response relationships are summarized in Table 22. Four of the six dosage response relationships were statistically reliable. The SEL value of indoor noise events successfully predicted sleep disturbance by all three criteria, and the SEL value of outdoor noise events successfully predicted behavioral awakenings as confirmed by button pushes.

**Table 22** Summary of dosage-response correlations for events occurring between 2200 and 0700 hours. (Data aggregated over all nights).

| MEASURE OF SLEEP DISTURBANCE | CRITERION FOR SLEEP DISTURBANCE       | NUMBER OF INDOOR NOISE EVENTS | NUMBER OF OUTDOOR NOISE EVENTS | NOISE MEASUREMENT LOCATION               |   |
|------------------------------|---------------------------------------|-------------------------------|--------------------------------|--|---|
|                              |                                       |                               |                                | Indoor criterion, based on 19,158 events | Outdoor criterion, based on 24,543 events |
| Motility                     | Actimeter (zero crossings)            | 19,158                        | 16,669                         | .76*                                     | NS  |
| Arousal                      | Cole <i>et al.</i> (1992) (Actimeter) | 6,715                         | 17,449                         | .66*                                     | NS  |
| Awakening                    | Behavioral awakening response         | 8,892                         | 24,543                         | .75*                                     | .68*                                      |

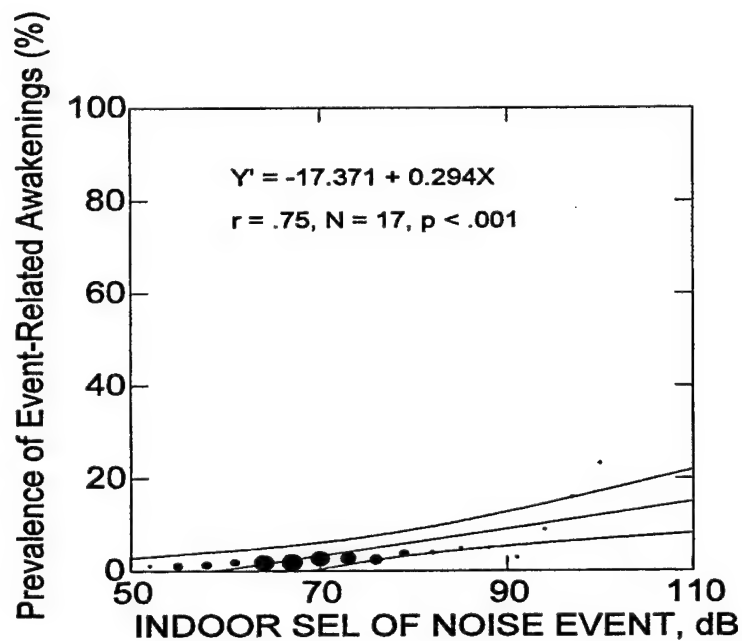
\*  $p < .005$ , one-sided test

NS: Not significantly different from a correlation of 0

Figure 31 shows that indoor SEL of noise events predicted behavioral awakening moderately well,  $r(15) = .75$ ,  $p < .001$ . The probability of arousal increased by about 3% with each 10 dB increase in SEL. Polynomial regression revealed statistically reliable quadratic and cubic relationships ( $p < .001$ ), with multiple  $R$  increasing to .89 with inclusion of the quadratic trend and to .96 with inclusion of the cubic trend. For ease of comparison with other dosage-response relationships, however, the linear fit is shown in the figure.

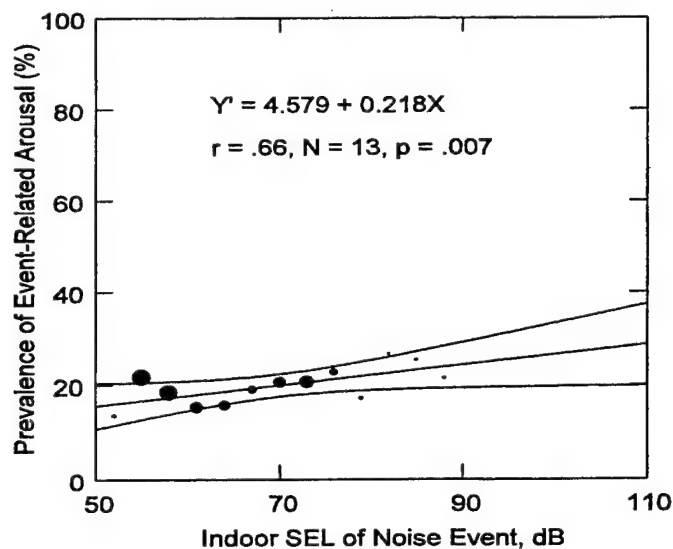
Figure 32 shows that indoor SEL of noise events predicted arousal moderately well,  $r(11) = .66$ ,  $p = .007$ . The probability of arousal increased by about 2% with each 10 dB increase

in SEL. Polynomial regression revealed no statistically reliable quadratic or cubic relationships.



**Figure 31**

Prevalence of behavioral awakening responses aggregated by test participants in 3 dB intervals of indoor noise measurements. Curved lines bound the 95% confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events.



**Figure 32** Prevalence of arousal responses aggregated by test participants in 3 dB intervals of indoor noise measurements. Curved lines bound the 95% confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events.

Figure 33 shows that indoor SEL of noise events predicted motility moderately well,  $r(11) = .76, p = .001$ . The probability of arousal increased by about 4% with each 10 dB increase in SEL. Polynomial regression revealed no statistically reliable quadratic or cubic relationships.

Figure 34 shows that outdoor SEL of noise events predicted behavioral awakening moderately well,  $r(16) = .68, p = .001$ . However, the probability of arousal increased by less than 1% with each 10 dB increase in SEL. Polynomial regression revealed statistically reliable quadratic and cubic relationships ( $p < .005$ ), with multiple  $R$  increasing to .81 with inclusion of the quadratic trend and to .90 with inclusion of the cubic trend. For ease of comparison with other dosage-response relationships, however, the linear fit is shown in the figure.

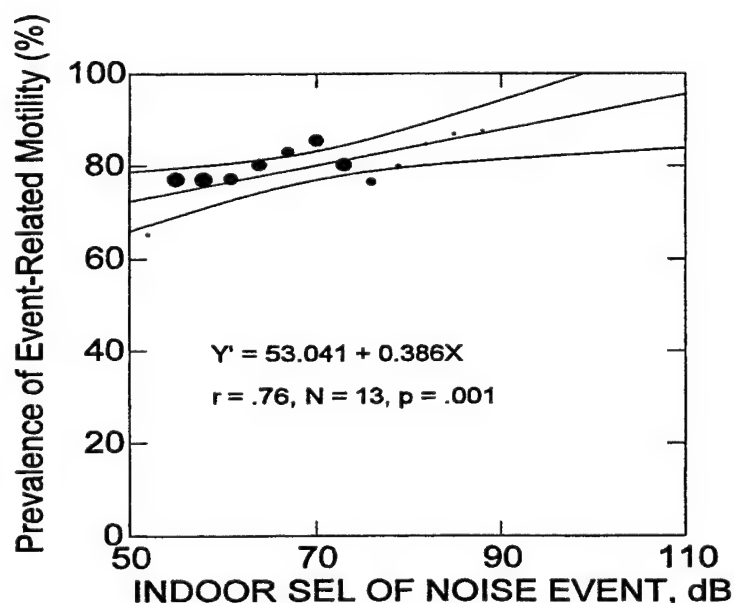
## G.2 PREDICTING SLEEP DISTURBANCE FROM NOISE LEVEL AND CONTROL VARIABLES

Direct logistic regression analysis was employed to predict sleep disturbance following noise events from the levels of the noise events, ambient noise levels, personal characteristics of respondents, time-related characteristics, and rating of tiredness the previous evening. Logistic regression is an appropriate analytic tool when the predicted variable represents the probability of an outcome (in this case whether sleep is disturbed) and predictor variables are a mixture of discrete and continuous measures.

Noise events used were those occurring between 2200 and 0700 hours; each event constituted

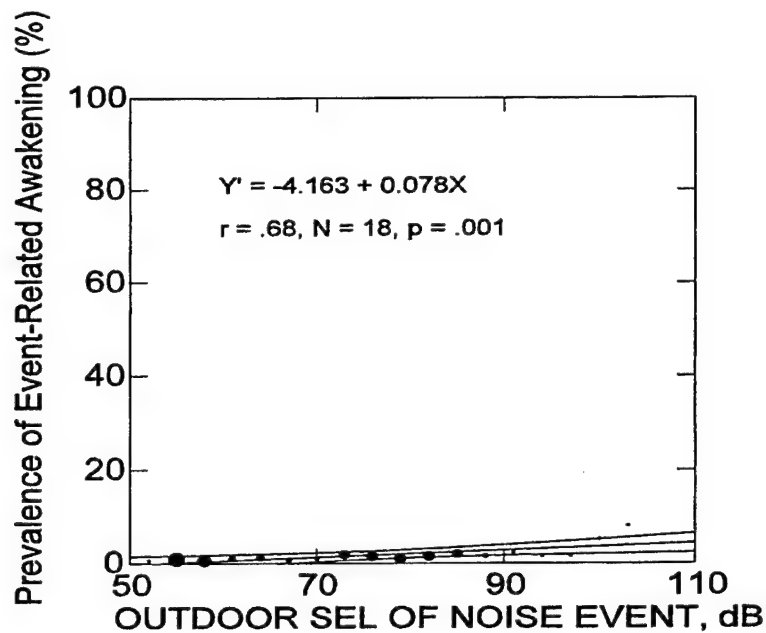
a case for analysis. The measures of sleep disturbance were the four that showed a statistically significant dosage-response relationships: behavioral awakening responses, arousals, and motility with noise measured indoors and behavioral awakening responses with noise measured outdoors. Type I error rate was controlled by setting  $\alpha = .001$  for each predictor. Contribution of each predictor variable is assessed after controlling for all other predictor variables in direct logistic regression.

Predictors included two sound level measures: SEL of noise events and TAVA of ambient level in sleeping quarters. Personal characteristics included gender, the linear effect of years of age, the quadratic effect of age (in which younger and older participants were combined and compared with participants 35-49 years of age), and spontaneous (non-event related) numbers of awakenings for the night in which the event occurred. This latter measure was poorly distributed, so a transform of it was used in analysis, in which the inverse was taken of spontaneous number of awakenings + 1, and then the measure was reflected (*i.e.*, the analyzed measure was 1 minus the inverse) to correspond with the direction of the original measure.



**Figure 33**

Prevalence of motility responses aggregated by test participants in 3 dB intervals of indoor noise measurements. Curved lines bound the 95% confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events.



**Figure 34** Prevalence of behavioral awakening responses aggregated by test participants in 3 dB intervals of outdoor noise measurements. Curved lines bound the 95% confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events.

Time-related characteristics were time since retiring in 15-m intervals, duration of residence in months, and study duration as indicated by number of nights in the study when the event occurred. A final predictor was a rating of tiredness during the previous day, on a scale of 1-5 in which 1 indicated not at all tired and 5 indicated extremely tired.

Table 23 summarizes the results of the logistic regression analyses. Noise events considered were those for which data were available for all 10 predictors and the sleep disturbance measure of interest.

**Table 23** Summary of logistic regression analyses of behavioral awakenings, arousals and motility by SEL of individual events and additional predictors.

| LOCATION OF NOISE MEASUREMENT  | INDOORS   |  |   | OUTDOORS   |
|--|---|--|---|--|
| Response   | Behavioral Awakening  | Arousal  | Motility  | Behavioral Awakening                                 |
| Number of events with disturbance / total events                                   | 507 / 18,192  | 1,183 / 5,961  | 1,466 / 7,926   | 301 / 23,445   |
| Significant predictors (each adjusted for all others)                              | SEL, ambient level, time since retiring, spontaneous awakenings | Ambient level, tiredness, nights, gender, spontaneous awakenings | SEL, ambient level, tiredness, time since retiring, duration of residence, gender, spontaneous awakenings | SEL, tiredness, age (linear), spontaneous awakenings |
| Full model (10 predictors)<br>Variance accounted for<br>Prediction success<br>$d'$ | 9%<br>95%<br>0.75   | 3%<br>69%<br>0.62  | 8%<br>72%<br>0.69   | 4%<br>98%<br>unavailable                             |
| SEL alone<br>Variance accounted for<br>Prediction success<br>$d'$                  | 4%<br>95%<br>0.62   | NS<br>NS<br>NS   | NS<br>NS<br>NS  | 1%<br>98%<br>unavailable                             |
| Average SEL that did / did not disturb sleep                                       | 71 dB / 76 dB   | NS   | NS  | 72 dB / 76 dB  |

NS: Not statistically significant at  $\alpha = .001$

## G.2.1 Prediction of Behavioral Awakening

### G.2.1.1 Indoor noise measurements

Data for the analysis were provided by all participants, responding to a total of 18,192 noise events recorded outdoors, occurring between 2200 and 0700 hours.

The combination of 10 variables reliably predicted behavioral awakening responses as recorded by a button push, with a model produced by those variables better than a chance model,  $\chi^2(10) = 427.96, p < .001$ . Four variables significantly added to the remaining variables in prediction of arousal: spontaneous awakening rate, time since retiring, ambient level, and SEL of noise event, as seen in Table 24.

Spontaneous awakening rate (after inverting and reflecting to compensate for severe skewness) was *negatively* associated with button pushes; *i.e.*, the lower the spontaneous rate of awakening, the greater the likelihood of awakening in the presence of a noise event. Probability of awakening *increased* by about 4% with each subsequent 15-minute period over the course of the night. Probability of awakening decreased by about 5% with each dB increase in ambient level, and increased by about 6% with each dB increase in SEL of the noise event.

**Table 24** Prediction of an awakening by button push following within 5 minutes of noise events recorded indoors between 2200 and 0700 hours (combined data).

| VARIABLE (UNIT)   | B      | ODDS RATIO<br>PER UNIT | 95% CONFIDENCE INTERVAL<br>FOR ODDS RATIO |       | F TO REMOVE<br>df=1, 18,181 |
|---|--------|------------------------|---|-------|-----------------------------|
|   |        |                        | Lower                                     | Upper |                             |
| Personal Characteristics                                  |        |                        |   |       |                             |
| Number of spontaneous awakenings (inverted and reflected) | -0.660 | 0.52                   | 0.38                                      | 0.70  | 20.22 *                     |
| Gender  | 0.173  | 1.19                   | 0.99                                      | 1.43  | 3.52                        |
| Age (linear, years)                                       | -0.006 | 0.99                   | 0.99                                      | 1.00  | 2.17                        |
| Age (quadratic, 35-49 vs. others)                         | -0.321 | 0.73                   | 0.59                                      | 0.89  | 10.11                       |
| Time-Related Characteristics                              |        |                        |   |       |                             |
| Time since retiring (in 15 minute increments)             | 0.041  | 1.04                   | 1.03                                      | 1.05  | 105.36 *                    |
| Duration of residence (months)                            | 0.001  | 1.00                   | 1.00                                      | 1.00  | 7.56                        |
| Number of nights in study                                 | -0.005 | 1.00                   | 0.98                                      | 1.01  | 1.04                        |
| Pre-Sleep Characteristics                                 |        |                        |   |       |                             |
| Tiredness on retiring (scale of 1 to 5)                   | 0.140  | 1.15                   | 1.05                                      | 1.26  | 9.90                        |
| Noise Characteristics                                     |        |                        |   |       |                             |
| Ambient level (dB)  | -0.015 | 0.95                   | 0.94                                      | 0.96  | 101.60 *                    |
| SEL (dB)  | 0.060  | 1.06                   | 1.05                                      | 1.07  | 209.30 *                    |

\*  $p < .001$

The prediction success rate of 95% for the full model reflects the rarity of noise events that elicited button push responses: 507 out of 18,192. Using McFadden's  $\rho^2$  criterion, the model accounted for 9% of the variance in arousal. Prediction success by SEL alone remained 95%, in a model that was reliably better than chance,  $\chi^2(1) = 164.30, p < .001$ . However, SEL alone accounted for only 4% of the variance in awakening responses.

The performance of the logistic regression model in predicting the presence of an awakening response may be summarized by a receiving operating characteristic (ROC) curve. An ROC curve plots the probability of a correct decision — a “hit” — against the probability of an incorrect decision — a “false alarm” — to show the entire range of performance (ratios of hits to false alarms) that a decision maker (a statistical prediction model, in this case) can exhibit. The area under the ROC curve,  $d'$ , is a measure of the detectability of awakening by the model. The ROC curve for the performance of SEL alone as a predictor had a  $d' = 0.62$ , whereas the ROC curve for the performance of a model based on all of the predictor variables had a  $d' = 0.75$ .

### G.2.1.2 Outdoor noise measurements

Data for the analysis were provided by all participants, responding to a total of 23,445 noise events recorded outdoors, occurring between 2200 and 0700 hours.

The combination of 10 variables reliably predicted awakening as recorded by button pushes, with a model produced by those variables better than a chance model,  $\chi^2(10) = 128.60, p < .001$ . Four variables significantly added to the remaining variables in prediction of awakening: spontaneous awakening rate, age, tiredness, and SEL of the noise event, as seen in Table 25. Spontaneous awakening rate (after inverting and reflecting to compensate for severe skewness) was associated with behavioral awakening; the greater the spontaneous rate of awakening, the greater the likelihood of awakening in the presence of a noise event. Probability of awakening increased by about 2% with each succeeding year of age, and by about 34% with each increment of one scale unit of tiredness. An increase of 1 dB in SEL increased probability of awakening by about 3%.

**Table 25** Prediction of an awakening by button push following within 5 minutes of noise events recorded outdoors between 2200 and 0700 hours.

| VARIABLE (UNIT)   | B      | ODDS RATIO<br>PER UNIT | 95% CONFIDENCE INTERVAL<br>FOR ODDS RATIO |       | F RATIO<br>(WALD TEST)<br>df=1, 23,434 |
|---|--------|------------------------|---|-------|--|
|   |        |                        | Lower                                     | Upper |  |
| Personal Characteristics                                  |        |                        |   |       |  |
| Number of spontaneous awakenings (inverted and reflected) | 0.956  | 2.60                   | 1.73                                      | 3.91  | 21.25 *                                |
| Gender  | -0.095 | 0.91                   | 0.72                                      | 1.15  | 0.64                                   |
| Age (linear, years)                                       | 0.022  | 1.02                   | 1.01                                      | 1.03  | 14.91 *                                |
| Age (quadratic, 35-49 vs. others)                         | 0.240  | 1.27                   | 0.99                                      | 1.63  | <0.01                                  |
| Time-Related Characteristics                              |        |                        |   |       |  |
| Time since retiring (in 15 minute increments)             | 0.014  | 1.02                   | 1.00                                      | 1.03  | 7.24                                   |
| Duration of residence (months)                            | -0.001 | 1.00                   | 1.00                                      | 1.00  | 2.46                                   |
| Number of nights in study                                 | -0.016 | 1.01                   | 1.01                                      | 1.02  | 6.22                                   |
| Pre-Sleep Characteristics                                 |        |                        |   |       |  |
| Tiredness on retiring (scale of 1 to 5)                   | 0.292  | 1.34                   | 1.20                                      | 1.49  | 27.16 *                                |
| Noise Characteristics                                     |        |                        |   |       |  |
| Ambient level (dB)  | 0.003  | 1.00                   | 0.99                                      | 1.02  | 0.12                                   |
| SEL (dB)  | 0.025  | 1.03                   | 1.03                                      | 1.04  | 21.25 *                                |

\*  $p < .001$  (Wald test used because very large sample size rendered test of  $F$  to remove impractical)

The prediction success rate of 98% for the full model reflects the extreme rarity of noise events that elicited behavioral awakening responses: 301 out of 23,445. Using McFadden's  $\rho^2$  criterion, the model accounted for 4% of the variance in awakening. Prediction of success was about

the same for a model including on SEL, again because of event rarity. The reduced model accounted for only about 1% of the variance in awakening. However, it was significantly better than a chance model,  $\chi^2(1) = 33.53, p > .001$ . ROC analysis of awakening was not feasible because of the very large number of noise events.

### **G.2.2 Prediction of Arousals**

As seen in Table 22, arousals as defined by Cole *et al.*'s (1992) actimetric criterion were successfully predicted by indoor but not by outdoor noise events. Data for the logistic regression analysis of arousals were provided by 5,961 noise events recorded indoors, occurring between 2200 and 0700 hours.

The combination of 10 variables reliably predicted arousals, with a model produced by those variables better than a chance model,  $\chi^2(10) = 155.97, p < .001$ . Five variables significantly added to the remaining variables in prediction of arousals: spontaneous awakening rate, gender, tiredness, and ambient level, as seen in Table 26. Spontaneous awakening rate (after inverting and reflecting to compensate for severe skewness) was negatively associated with arousals; *i.e.*, the greater the spontaneous rate of awakening, the less the likelihood of an arousal response in the presence of a noise event. Women were about 21% more likely to exhibit an arousal response in the presence of an outdoor noise event. Arousals were about 1% less likely with each succeeding night in the study. Probability of arousals decreased by about 11% with each increment of one scale unit of tiredness. Each increase of 1 dB in ambient level decreased the probability of arousals in the presence of a noise event by about 2%. SEL of outdoor events did not reliably predict arousals after taking into account the remaining nine predictors, nor did SEL alone successfully predict arousals in this data set. (Note that the linear regression on aggregated data provides more statistical power than these logistic regression analyses.)

The prediction success rate for arousals was 69% for the full model. Using McFadden's  $\rho^2$  criterion, the model accounted for 3% of the variance in arousal responses. ROC analysis indicated  $d' = 0.62$  for the detectability of arousals by the model including all 10 predictors.

### **G.2.3 Prediction of Motility**

As seen in Table 22, actimetrically defined motility was successfully predicted by indoor but not outdoor noise events. (Arousals are based on a different criterion for these same actimetric responses.) Data for the logistic regression analysis of motility were provided by 7,926 noise events recorded indoors, occurring between 2200 and 0700 hours.

Table 26

Prediction of an arousal as defined by Cole *et al.* (1992) following events recorded indoors between 2200 and 0700 hours.

| VARIABLE (UNIT)   | B      | ODDS RATIO<br>PER UNIT | 95% CONFIDENCE INTERVAL<br>FOR ODDS RATIO |       | F TO REMOVE<br><br>df=1, 5,950 |
|---|--------|------------------------|---|-------|--------------------------------|
|   |        |                        | Lower                                     | Upper |                                |
| Personal Characteristics                                  |        |                        |   |       |                                |
| Number of spontaneous awakenings (inverted and reflected) | -0.565 | 0.57                   | 0.19                                      | 0.45  | 23.71 *                        |
| Gender  | -0.238 | 0.79                   | 0.69                                      | 0.90  | 11.54 *                        |
| Age (linear, years)                                       | 0.011  | 1.01                   | 1.00                                      | 1.02  | 6.78                           |
| Age (quadratic, 35-49 vs. others)                         | 0.155  | 1.17                   | 1.00                                      | 1.36  | 4.10                           |
| Time-Related Characteristics                              |        |                        |   |       |                                |
| Time since retiring (in 15 minute increments)             | 0.005  | 1.00                   | 1.00                                      | 1.00  | 2.16                           |
| Duration of residence (months)                            | 0.000  | 1.00                   | 1.00                                      | 1.00  | 1.50                           |
| Number of nights in study                                 | 0.013  | 1.01                   | 1.01                                      | 1.02  | 14.07 *                        |
| Pre-Sleep Characteristics                                 |        |                        |   |       |                                |
| Tiredness on retiring (scale of 1 to 5)                   | -0.114 | 0.89                   | 0.84                                      | 0.95  | 12.40 *                        |
| Noise Characteristics                                     |        |                        |   |       |                                |
| Ambient level (dB)  | -0.019 | 0.98                   | 0.98                                      | 0.99  | 36.67 *                        |
| SEL (dB)  | 0.007  | 1.01                   | 1.00                                      | 1.02  | 2.76                           |

\*  $p < .001$

The combination of 10 variables reliably predicted motility, with a model produced by those variables better than a chance model,  $\chi^2(10) = 577.04$ ,  $p < .001$ . Seven variables significantly added to the remaining variables in prediction of motility: spontaneous awakening rate, gender, time since retiring, duration of residence, tiredness, ambient level, and SEL of the noise event, as seen in Table 27. Spontaneous awakening rate (after inverting and reflecting to compensate for severe skewness) was negatively associated with motility; the greater the spontaneous rate of awakening, the less the likelihood of motility in the presence of a noise event. Men were about 40% *more* likely to move in the presence of an outdoor noise event. For each succeeding 15 minutes over the night, the probability of motility increased by about 5%. Probability of movement in the presence of a noise event decreased with duration of residence, but the effect was less than 1% per month.

Probability of motility decreased by about 10% with each increment of one scale unit of tiredness. Each increase of 1 dB in ambient level decreased the probability of awakening in the presence of a noise event by about 2%. An increase of 1 dB in SEL of a noise event increased motility by about 2% after adjustment for the nine other predictors. However, SEL of outdoor events alone did not successfully predict arousals in this data set. (As noted for the arousal data based on outdoor events, the linear regression on aggregated data provides more statistical power than these logistic regression analyses.)

The prediction success rate for motility was 72% for the full model. Using McFadden's  $\rho^2$

criterion, the model accounted for 8% of the variance in motility responses. ROC analysis indicated  $d' = 0.69$  for the detectability of motility by the model including all 10 predictors.

**Table 27** Prediction of motility following events recorded indoors between 2200 and 0700 hours.

| VARIABLE (UNIT)   | B      | ODDS RATIO<br>PER UNIT | 95% CONFIDENCE INTERVAL<br>FOR ODDS RATIO |       | F TO REMOVE<br>df=1, 7,915 |
|---|--------|------------------------|---|-------|----------------------------|
|   |        |                        | Lower                                     | Upper |                            |
| Personal Characteristics                                  |        |                        |   |       |                            |
| Number of spontaneous awakenings (inverted and reflected) | -0.688 | 0.50                   | 0.41                                      | 0.62  | 43.74 *                    |
| Gender  | 0.328  | 1.39                   | 1.22                                      | 1.58  | 24.97 *                    |
| Age (linear, years)                                       | -0.002 | 1.00                   | 0.99                                      | 1.01  | 0.31                       |
| Age (quadratic, 35-49 vs. others)                         | 0.140  | 1.16                   | 1.01                                      | 1.33  | 4.17                       |
| Time-Related Characteristics                              |        |                        |   |       |                            |
| Time since retiring (in 15 minute increments)             | 0.048  | 1.05                   | 1.04                                      | 1.06  | 252.28 *                   |
| Duration of residence (months)                            | -0.002 | 1.00                   | 1.00                                      | 1.00  | 22.84 *                    |
| Number of nights in study                                 | 0.008  | 1.01                   | 1.00                                      | 1.02  | 6.53                       |
| Pre-Sleep Characteristics                                 |        |                        |   |       |                            |
| Tiredness on retiring (scale of 1 to 5)                   | -0.101 | 0.90                   | 0.86                                      | 0.96  | 13.06 *                    |
| Noise Characteristics                                     |        |                        |   |       |                            |
| Ambient level (dB)  | -0.021 | 0.98                   | 0.97                                      | 0.99  | 50.19 *                    |
| SEL (dB)  | 0.021  | 1.02                   | 1.01                                      | 1.03  | 28.13 *                    |

\*  $p < .001$